(NASA-CR-134970) EXPERIMENTAL CLEAN COMBUSTOR PROGRAM, PHASE 2 (Pratt and Whitney Aircraft) 86 p HC $5.00 CSCL 21D
N76-28429
Unclas
G3/28 47976

NASA CR-134970
PWA-5370

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM
PHASE II
ALTERNATE FUELS ADDENDUM

by

R. Roberts, A. Peduzzi, G. E. Vitti

PRATT & WHITNEY AIRCRAFT DIVISION
UNITED TECHNOLOGIES CORPORATION

July 1976

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA-Lewis Research Center
Contract NAS3-18544

PRATT & WHITNEY AIRCRAFT

East Hartford, Connecticut 06108

In reply please refer to:
RR:JR:lpk-EB-2F

16 August 1976

To:	National Aeronautics and Space Administration Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135
Attention:	Mr. Richard Niedzwiecki (MS 60-6)
Subject:	Final Report on the Experimental Clean Combustor Program, Phase II, Alternate Fuels Addendum
Reference:	Contract NAS3-18544, Modifications No. 2 and 3

The subject report is forwarded in compliance with the referenced contract. Distribution is being made in accordance with the list appearing on the last pages of the report.

The report was prepared under the Contractor's reference number PWA-5370.

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Division

R. Roberts

R. Roberts
Program Manager

cc: NASA-Lewis Research Center
Cleveland, Ohio 44135
Attention: L. Schopen (MS 500-206)

NAVPRO, Pratt & Whitney Aircraft
East Hartford, Connecticut 06108

1. Report No. CR-134970	2 Government Accession No.	3 Recipient's Catalog No.
4. Title and Subtitle Alternate Fuels Addendum, Experimental Clean Combustor Program, Phase II		5. Report Date July 1976
		6 Performing Organization Code
7 Author(s) R. Roberts, A. Peduzzi, G. E. Vitti		8. Performing Organization Report No. PWA-5370
		10 Work Unit No
9. Performing Organization Name and Address Pratt & Whitney Aircraft Division United Technologies Corporation East Hartford, Connecticut 06108		11. Contract or Grant No. NAS3-18544, Mods. 2 and 3
		13 Type of Report and Period Covered Contract Report
12. Sponsoring Agency Name and Address National Aeronautical and Space Administration Lewis Research Center 21000 Brookpark Road, Cleveland, Ohio 44135		14 Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

An Alternate Fuels investigation was conducted as an addendum to Phase II of the NASA Experimental Clean Combustor Program. The objective was to experimentally determine the impacts, if any, on exhaust emissions, performance, and durability characteristics of the Hybrid and Vorbix low-pollution combustor concepts when operated on test fuels which simulate composition and property changes which might result from future broadened aviation turbine fuel specifications or use of synthetically derived crude feedstocks. Results of the program indicate a significant increase in CO and small NO_x increase in emissions at Idle for both combustor concepts, and an increase in THC for the Vorbix concept. Minimal impact was observed on gaseous emissions at high power. The Vorbix concept exhibited significant increase in exhaust smoke with increasing fuel aromatic content. Altitude stability was not affected for the Vorbix combustor, but was substantially reduced for the Hybrid concept. Severe carbon deposition was observed in both combustors following limited endurance testing with No. 2 Home Heat fuel. Liner temperature levels were insensitive to variations in aromatic content over the range of conditions investigated.

17. Key Words (Suggested by Author(s)) Main Burner Emissions, Alternate Fuels, Synthetic Fuels, Experimental Clean Combustor Program	18 Distribution Statement		
19 Security Classif (of this report) Unclassified	20 Security Classif. (of this page) Unclassified	21. No. of Pages 79	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA-C-168 (Rev. 6-71)

FOREWORD

This document describes work conducted and completed by Pratt & Whitney Aircraft Division of United Technologies Corporation under the Alternate Fuels Addendum to Phase II of the Experimental Clean Combustor Program. This final report was prepared for the National Aeronautics and Space Administration (NASA) Lewis Research Center in compliance with the requirements of Modifications No. 2 and No. 3 of Contract NAS3-18544.

The authors of this report wish to acknowledge the guidance and assistance provided by Messrs. J. Grobman and R. Niedzwiecki of the NASA Lewis Research Center and Mr. A. R. Marsh of Pratt & Whitney Aircraft.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

SUMMARY

An experimental program was conducted to investigate exhaust emissions, performance, and durability characteristics of advanced technology, low-pollution combustors operating with fuels which represent composition and physical property changes which might result from future broadened aviation turbine fuel specifications or use of synthetically derived crude feedstocks. The scope of the program was restricted to investigation of increases in final boiling point and aromatic content. The four test fuels included commercial grade No. 2 Diesel and No. 2 Home Heat oils and specially prepared blends of Jet A with Xylene and with Naphthalene blending stocks. The Alternate Fuels program was conducted as an addendum to the Experimental Clean Combustor Program (ECCP), Phase II, and the technical effort was integrated with the ECCP testing to allow back-to-back evaluation of the test fuels and the baseline Jet A fuel. The program included evaluation of the Hybrid and Vorbix combustor concepts.

Results of the program indicate a significant increase in CO and a small increase in NO_x emissions at Idle. In the case of the Vorbix combustor, THC emissions increased at the simulated Idle condition when using the subject fuels. Minimal difference in gaseous emission levels was observed at high power. The two combustor concepts exhibited different responses in exhaust smoke level and altitude stability. Exhaust smoke increased with increasing fuel aromatic content for the Vorbix combustor, which employs direct liquid fuel injection pilot and main zone designs. The Hybrid combustor, which employs intrinsically low smoke, premix-type burning zones, exhibited no significant increase in exhaust smoke. Altitude stability (blow out) was not affected for the Vorbix combustor, but was substantially reduced relative to the Jet A baseline for the Hybrid concept.

Severe carbon deposition was observed in both combustors following the limited endurance testing using No. 2 Home Heat fuel, indicating a potentially detrimental effect on engine hot section durability. No consistent trend to increased liner temperature was indicated with increasing fuel aromatic content.

INTRODUCTION

This report presents exhaust gas emissions, engine performance, and component durability measurements from two advanced-technology, low-emission combustor concepts operated with four special fuels and Jet A fuel. The objective of the program is to provide a preliminary assessment of the pollution and performance impact of broadened fuel specifications for combustors designed to attain Environmental Protection Agency (EPA) standards. The scope of this program was limited to investigation of two specific changes to current aviation turbine fuel specifications, increased aromatic concentration and increased final boiling point, both of which might be necessary for syncrude derived fuels.

The United States is currently importing approximately thirty percent of the petroleum consumed in this country. Continuing depletion of domestic crude oil reserves makes it highly desirable that substitute fuels be developed from other resources such as shale oil or coal. Since aviation gas turbine fuels represent a significant percentage of the total petroleum consumption in the United States, it is appropriate that fuels produced from non-petroleum sources be considered for this application. Due to economic and other considerations, synthetic fuels may not meet present aviation turbine fuel specifications. In addition, a broadening of these specifications would permit a relative increase in supply from petroleum feedstocks. Although broadening of the fuel specifications may increase the supply of aviation turbine fuels, it may also incur penalties to exhaust gas emissions, engine performance, and/or component durability.

The Alternate Fuels program was conducted as an addendum to the NASA/P&WA Experimental Clean Combustor Program, Phase II (Reference 1). Testing of the subject fuels was conducted on two advanced combustor concepts (the Vorbix concept and the Hybrid concept) following evaluation under the basic ECCP Phase II program. American Society for Testing Materials (ASTM) Jet A fuel was used as a baseline for comparison purposes. Testing was conducted in a 90-degree sector test rig simulating the JT9D engine combustor envelope and at simulated engine Idle and Sea Level Take-Off (SLTO) conditions. All combustor inlet conditions were the same as those produced in the engine except for inlet pressure at SLTO, which was limited to 6.8 atmospheres by test facility airflow capacity. The corresponding inlet pressure produced in the engine is 21.7 atmospheres. Suitable correction factors were applied to the gaseous emission data to account for this difference. Smoke levels are presented as measured rig values.

CHAPTER I PROGRAM DESCRIPTION

The Alternate Fuels program was conducted concurrently with, and as an addendum to, the Experimental Clean Combustor Program (ECCP) Phase II, Contract NAS3-18544, during the last six months of 1975. The program was aimed at investigating exhaust emissions, performance, and durability aspects of low pollution combustors operating with test fuels that simulate specific characteristics of possible synthetic and petroleum fuels with broadened specifications. The four test fuels, No. 2 Diesel, No. 2 Home Heat, Jet A + Xylene bottoms, and Jet A + Naphthalene blending stock, were chosen to provide indications of the effects of increased boiling point and increased aromatic content (lower percent hydrogen).

The major program tasks included high pressure screening tests of the Hybrid and Vorbix concepts with the four test fuels, altitude relight tests with the No. 2 Home Heat fuel, and high pressure endurance testing, again with the No. 2 Home Heat fuel.

The screening tests were conducted at the high pressure test facility, test stand X-903. The Hybrid and Vorbix combustor concepts were evaluated at simulated Idle and Sea Level Take-Off conditions with the four test fuels and the baseline fuel, Jet A. Data acquired included emissions, performance characteristics such as Idle stability and pattern factor, and liner temperature data.

Following the fuels screening tests at the high pressure facility, both combustor concepts were tested at the altitude relight test facility, stand X-306. No. 2 Home Heat fuel was selected for these tests since this fuel was expected to exhibit the greatest deficiency due to the combined increases in aromatic content and final boiling point.

The Hybrid and Vorbix combustors were then returned to the high pressure test facility for endurance testing. Each combustor concept was modified in a manner dictated by the pollution reduction and performance objectives of the basic Phase II program, consistent with improvement of problem areas identified in the alternate fuels screening tests. The endurance testing consisted of four hours of continuous operation at SLTO, followed by visual hardware inspection, and four hours of operation at Idle conditions. No. 2 Home Heat was chosen as the test fuel because it represented the combination of properties expected to have the greatest impact on durability. The endurance testing was intended to indicate carbon deposition and nozzle coking problems rather than to predict areas of long term hardware deterioration.

CHAPTER II EQUIPMENT AND EXPERIMENTAL PROCEDURES

A. Test Combustors

The evaluation of the four subject fuels was conducted on Hybrid combustor configuration H-6 and the Vorbix combustor configuration S-20. Endurance testing with No. 2 Home Heat fuel was conducted on Hybrid combustor configuration H-7 and the Vorbix combustor configuration S-22. All testing was conducted in 90-degree sector rigs simulating the JT9D engine combustor envelope. Design features of the Phase II ECCP Hybrid and Vorbix combustor concepts are shown in Figures 1 and 2, respectively. A more detailed description of each combustor concept is provided in the ECCP Phase II Final Report (Reference 1). Specific design information, including liner hole area distribution, is contained in Appendix A.

Hybrid combustor configuration H-6 utilized hollow-cone, pressure atomizing pilot nozzles and low ΔP main fuel injectors. This configuration had no pilot or main dilution air, but had increased pilot flameholder and main zone bulkhead cooling. Configuration H-7 differed from configuration H-6 in the substitution of solid-cone, pressure atomizing pilot fuel nozzles.

Both Vorbix combustor configurations S-20 and S-22 utilized pressure atomizing pilot and main fuel nozzles. The principal differences between these configurations were liner airflow distribution changes affected by modifications to the inlet hood geometry, revised pilot bulkhead cooling, and increased pilot airflow through use of a larger pilot swirler.

B. Fuels Description

The properties of synthetic aviation fuels will depend heavily on the raw materials available and the refining processes used. The four fuels selected for this program were intended to provide a cross section of possible synthetic fuel characteristics. Fuel properties specifically addressed in this program were aromatic content and final boiling point.

The four test fuels included:

- No. 2 Diesel (commercial grade)
- No. 2 Home Heat (commercial grade)
- Jet A + Xylene Blend
- Jet A + Naphthalene Blend

Analyses of the Jet A baseline and the subject fuels are presented in Table I.

The No. 2 Diesel and No. 2 Home Heat fuels tested were commercially available No. 2 oils. Both fuels had similar boiling ranges with a final boiling point 40 to 50 K higher than the Jet A specification (ASTM D-1655). Both fuels also contained higher aromatics than the Jet A specification, No. 2 Diesel with 27.0 percent and No. 2 Home Heat with 38.5 percent. The No. 2 Diesel and Home Heat fuels selected for this program provide two levels of

TABLE I

ANALYSIS OF TEST FUELS

	ASTM D-1655	P&WA TEST FUELS				
	Jet A Specification	Jet A Baseline	No. 2 Diesel	No. 2 Home Heat	Jet A + Xylene	Jet A + Naphthalene
Specific Gravity 289/289 K	0.7753–0.8398	0.8151	0.8519	0.8623	0.8358	0.8571
Viscosity @ 311K, (m^2/s)	–	1.57×10^{-6}	2.75×10^{-6}	2.32×10^{-6}	1.05×10^{-6}	1.50×10^{-6}
@ 292K, (m^2/s)	–	2.16×10^{-6}	4.23×10^{-6}	3.47×10^{-6}	1.37×10^{-6}	2.08×10^{-6}
Flash Point K	358	327	347	327	316	333
Heat of Combustion, Net (j/kg)	42.8×10^6 min	43.2×10^6	42.7×10^6	42.5×10^6	42.3×10^6	42.2×10^6
Freezing Point K	233	228	253	257	216	229
Sulfur (wt. %)	0.3 max	0.034	0.24	0.18	0.02	0.03
Nitrogen (ppm)	–	5	42	93	6	5
Aniline Point (K)	–	335	335	324	300	315
Luminometer Number	45 min	44	33	21	23	24
Distillation (K)						
Initial Boiling Point	–	441	456	437	422	442
10%	500 max	459	495	474	437	468
20%	–	467	508	493	442	476
30%	–	477	517	507	446	483
40%	–	483	524	518	451	487
50%	506 max	489	532	528	458	491
60%	–	496	540	538	468	495
70%	–	503	550	550	480	499
80%	–	513	562	561	493	505
90%	–	524	580	579	506	514
Final Boiling Point	561 max	548	605	607	533	536
Recovery (vol. %)	–	98.0	97.5	98.0	98.0	98.5
Residue (vol. %)	1.5 max	1.2	2.1	2.0	1.0	0.9
Loss (vol. %)	1.5 max	0.8	0.4	0.0	1.0	0.6
Aromatics (vol. %)	20 max	18.0	27.0	38.5	47.9	35.5
Olefins (vol. %)	–	0.4	0.3	0.7	0.5	0.4
Hydrogen (vol. %)	–	13.71	12.97	12.33	12.20	12.15
Hydrogen to Carbon Ratio	–	1.89:1	1.78:1	1.68:1	1.66:1	1.65:1
Naphthalenes (vol. %)	3.0	2.1	7.1	10.9	1.3	16.2

PRATT & WHITNEY AIRCRAFT

increased aromatic content relative to the Jet A baseline, at approximately constant final boiling point. The No. 2 Home Heat contained a higher percentage of complex naphthalenic aromatics and a significantly lower percent of hydrogen when compared to the Jet A baseline.

The two custom blended, Jet A based fuels were supplied by the Ashland Oil and Refining Company, Ashland, Kentucky. The first of these fuels was blended from an in-specification Jet A base fuel (approximately 65 percent) and a blend of alkyl-benzene aromatic components (approximately 35 percent), described as "xylene bottoms". The second of these fuels was blended from the same Jet A base fuel (approximately 75 percent) and a naphthalene charge stock (approximately 25 percent) containing greater than 50 percent naphthalene precursors. A representative analysis of the naphthalene stock used in the Jet A + Naphthalene blend is given in Table II below:

TABLE II

TYPICAL NAPHTHALENE BLENDING STOCK ANALYSIS

Component	Weight Percent
benzene, toluene, xylenes	3.0
alkyl aromatics (not naphthalenes)	13.7
indane	0.5
indene	4.3
tetralin	5.1
naphthalene	19.9
dimethyl naphthalene	33.1
biphenyl naphthalene	13.6
higher boiling naphthalenes	6.3
other	0.5

These aromatics might be expected in alternate gas turbine fuels since most either occur naturally or derive from conventional refining techniques.

The two blended fuels were chosen to simulate a synthetic fuel with a boiling range within the Jet A specification but with a percent hydrogen about 1.5 to 2.0 percent lower than a typical Jet A fuel. The aromatics exceeded the Jet A specification by magnitudes of two to three. The two blended fuels were designed to permit identification of the effect of aromatic type (simple versus complex) at approximately constant final boiling point and hydrogen content.

Certain other requirements of the Jet A specification, such as freezing point and luminometer number, as well as operational requirements such as resistance to thermal decomposition and oxidation, have not been met by the test fuels. For these reasons, the test fuels may not be representative of actual aircraft quality fuels having these values of final boiling point and aromatic content. In fact, relaxation of the final boiling point and aromatic content

may prove incompatible with maintenance of the other requirements of the Jet A specification. However, the fuels selected are in keeping with the program objective of discerning the first-order effects of relaxing current aviation turbine fuel specifications in the principal areas being addressed.

C. Test Facilities

The combustor tests were conducted in two test facilities. The emissions, performance, and endurance evaluations were conducted at X-903 stand, a high pressure test facility located at the P&WA branch plant in Middletown, Connecticut. Altitude stability and relight testing was conducted in an altitude test facility, stand X-306, located in East Hartford, Connecticut.

A detailed description of both facilities is presented in the ECCP Phase I Final Report (Reference 2). The only modification to the Middletown facility was the addition of portable storage tanks for the two Jet A fuel blends. Two existing on-site tanks were used to store the No. 2 Diesel and No. 2 Home Heat oils. Separate lines were plumbed to the test cell for the fuels tests. A constant displacement pump was used in conjunction with a return system to continuously circulate the fuel to ensure that the blended fuels remained well mixed. The capacity of the pump was eight to ten times that required for the test rig. Prior to testing each of the fuels, the common lines were flushed with the fuel to be tested and all filters were changed. A fuel sample was drawn at the test rig before each run for verification of the fuel quality.

Two 90-degree sector combustor rigs, fabricated during the ECCP Phase I, were modified for use during Phase II and the Fuels Addendum programs. A detailed description of the rig configuration is provided in the ECCP Phase I Final Report (Reference 2). A schematic diagram of a test rig and the adapting duct work installed in the test facility is shown in Figure 3.

D. Instrumentation

Both the high pressure test facility and the altitude test facility contained sufficient instrumentation to document the rig operating conditions. In addition to the basic instrumentation contained by both facilities, the high pressure facility contained an automatic-sequencing traversing probe located at the combustor exhaust plane to obtain temperature, pressure, and gas sampling information.

The altitude test facility was equipped with exit plane temperature instrumentation to permit determination of the lit or unlit status of the test combustor for altitude stability and relight testing. This facility also contained a closed-circuit television system to permit observation of the flame propagation after lighting. A detailed description of the gas analysis equipment, automatic data recording system, and other combustor instrumentation is provided in the ECCP Phase I Final Report (Reference 2). Specific improvements to the gas analysis equipment and the automatic-sequencing traverse rake systems installed for the Phase II test program are described in the ECCP Phase II Final Report (Reference 1).

Embedded liner thermocouples were utilized during the alternate fuels screening tests to measure liner temperatures as a function of changes in fuel composition and operating conditions. Liner thermocouple locations for the Hybrid and Vorbix test combustors are shown in Figures 4 and 5, respectively. Chromel-Alumel thermocouples were used. The thermocouple junctions were installed employing the "wedge-wire" technique illustrated in Figure 6. Since combustor durability is proportional to maximum liner temperature, the thermocouples were located in regions of expected highest temperature. Both louver lap-joint weld areas and single-thickness louver locations were utilized. Redundant instrumentation permitted a modest thermocouple failure rate to be absorbed.

E. Test Conditions and Procedures

The combustor rig test conditions were set to match the JT9D-7 design table engine conditions for SLTO and Idle as closely as possible. The Idle condition, run with simulation of compressor air bleed, was typical of engine conditions which would occur in an engine installed on an aircraft in service. Fuel-air ratio excursions were investigated at both SLTO and Idle conditions. The overall fuel-air ratio was varied from 0.006 to 0.016 at Idle and from 0.014 to 0.023 at SLTO.

The test rig conditions are listed in Table III below and are compared with the corresponding JT9D-7 engine conditions.

TABLE III

TEST RIG CONDITION AND ACTUAL JT9D-7
ENGINE CONDITIONS

	Bled Idle		Sea Level Take-Off	
	Rig	Engine	Rig	Engine
Compressor Exit Pressure (atm)	2.93	2.93	6.80	21.70
Compressor Exit Temperature (K)	428	428	769	769
Combustor Total Airflow (kg/s)	3.90	16.53	6.88	92.90
Combustor Fuel Flow (kg/s)	0.049	0.209	0.156	2.110
Fuel-Air Ratio	0.0126	0.0126	0.0227	0.0227

All operating conditions were duplicated except for the inlet pressure at SLTO conditions, which was limited by the test facility airflow capacity to 6.8 atmospheres. Test rig fuel and airflow rates are scaled to the nominal one-quarter sector rig.

Variation of the pilot-to-main fuel flow split was investigated for each combustor configuration using Jet A fuel as part of the basic Phase II test program. Pilot-to-main fuel split was varied while holding the total fuel flow constant. The resulting data provided a basis for determining the optimum fuel distribution between the pilot and main burners. The optimum pilot fuel-air ratio (pilot fuel flow divided by total burner airflow) was defined as that which provided the lowest value for the emissions index of oxides of nitrogen (EI NO_X) at 99+ percent efficiency. This pilot fuel-air ratio was then maintained constant for each combustor configuration during the subsequent special fuels tests. Overall fuel-air ratio was altered by varying main fuel flow only.

Altitude stability tests were conducted at simulated JT9D-7 engine windmilling conditions. Actual engine combustor inlet temperature and pressure conditions were simulated while fuel flow and airflow levels were scaled for the one-quarter sector rig. The range of simulated conditions is shown in Figure 7, defining the flight regime in which the engine is required to relight in the event of a blow out.

The Fuels Addendum testing was conducted concurrently with the ECCP Phase II program. The Alternate Fuels program was integrated with the main program to minimize cost and provide back-to-back tests of the baseline fuel (Jet A) and the subject fuels. Details of the high pressure and altitude stability test procedures implemented during the Fuels Addendum portion of the program are discussed in the ECCP Phase I and Phase II Final Reports (References 2 and 1). The endurance testing was conducted in two continuous four-hour segments for each combustor concept. Sea Level Take-Off power was evaluated first since pilot coking was expected to be more severe at Idle operation. Both combustors were visually inspected after the SLTO test to note any distress or carbon deposits. Following tests at the Idle condition, a detailed inspection of the combustors was made.

F. Emission and Performance Data Calculation Procedures

1. Emissions

Fuel-air ratio was calculated by two methods, from measured flow rates for air and fuel and using the carbon balance method in accordance with SAE ARP 1256 procedures, Reference 3. From the carbon balance fuel-air ratio and the volume concentration of pollutant, the emission index (EI) can be expressed as grams of pollutant per kilograms of fuel. The details of this calculation are discussed in the ECCP Phase II Final Report (Reference 1). The combustion efficiency was calculated on a deficit basis as described in Reference 2. The smoke numbers presented in this report have been obtained in accordance with procedures outlined in SAE ARP 1179, Reference 4, and the Federal Register, Reference 5. Details of the smoke measurement system are contained in Appendix A of the ECCP Phase I Final Report, (Reference 2).

2. Performance

A complete description of the performance data calculations is presented in the ECCP Phase II Final Report (Reference 1).

3. Extrapolation of Pollution Data to Engine Conditions

Due to facility airflow limitations, it was not possible to simulate combustor inlet pressure and airflow in the sector rig at the SLTO operating point. In addition, a small amount of variation in the setting of combustor inlet conditions was unavoidable for successive test fuels. Therefore, the emissions data for oxides of nitrogen (NO_x), carbon monoxide (CO), and hydrocarbons (THC), were corrected to full engine operating conditions to permit precise comparison of the results. The NO_x emission indices were corrected for pressure, reference velocity, combustor inlet temperature, combustor exit temperature, and ambient humidity. CO and THC were corrected for pressure only. Smoke data are presented as measured at the reduced pressure, rig operating conditions. The correlations used are as follows:

$$NO_x\ corr. = (NO_x\ meas.)\left(\frac{P_{t4}\ corr.}{P_{t4}\ meas.}\right)^{0.5}\left(\frac{V_{ref.\ meas.}}{V_{ref.\ corr.}}\right)\left(\frac{T_{t5}corr.}{T_{t5}\ meas.}\right)$$

(Reference 1)

$$\exp\left[0.0188\,(H_{meas.} - H_{corr.})\right] \quad \exp\left(\frac{T_{t4}\ corr. - T_{t4}\ meas.}{288}\right)$$

$$CO_{corr.} = (CO_{meas.})\left(\frac{P_{t4}\ meas.}{P_{t4}\ corr.}\right)$$

(Reference 6)

$$THC_{corr.} = (THC_{meas.})\left(\frac{P_{t4}\ meas.}{P_{t4}\ corr.}\right)$$

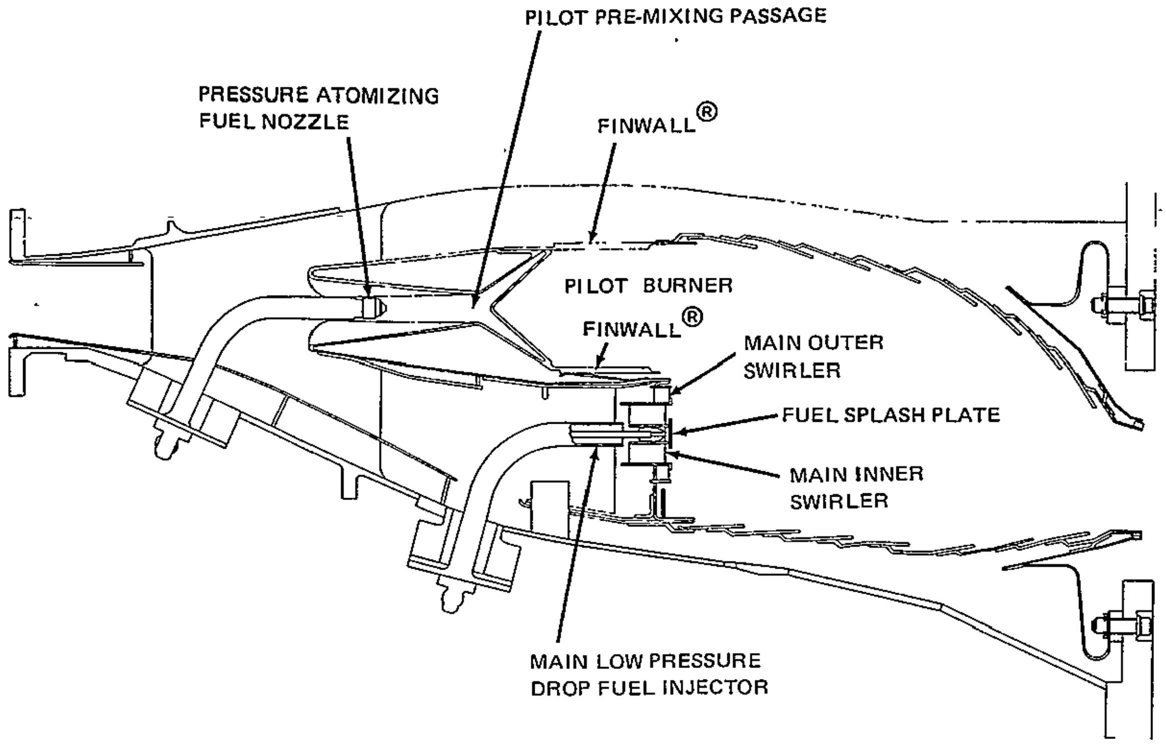
(Reference 6)

where:

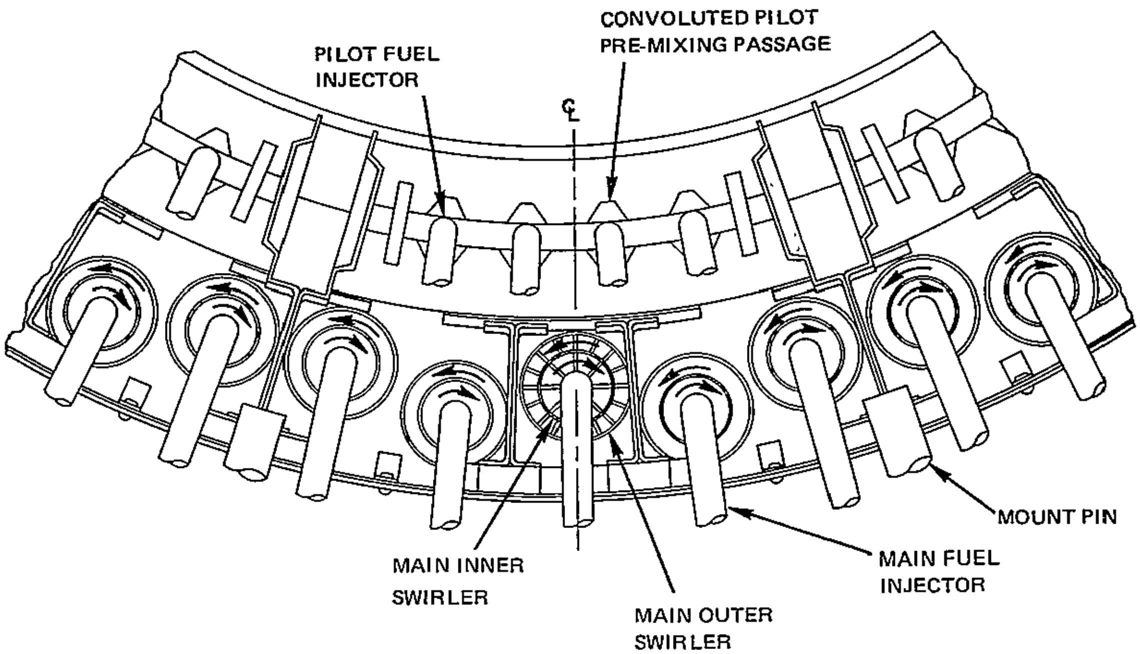
NO_x	=	Emission level of oxides of nitrogen, Equivalent NO_2 (g/kg fuel)
CO	=	Emission level of carbon monoxide (g/kg fuel)
THC	=	Emission level of total hydrocarbons, Equivalent CH_4 (g/kg fuel)
P_{t4}	=	Inlet total pressure (atm)
T_{t4}	=	Inlet total temperature (K)
$V_{ref.}$	=	Reference velocity (m/s)
H	=	Inlet specific humidity (g H_2O/kg air)
T_{t5}	=	Combustor exit temperature (K)

and subscripts:

corr.	=	Relates to value at corrected (engine) condition
meas.	=	Relates to value at measured (rig) condition

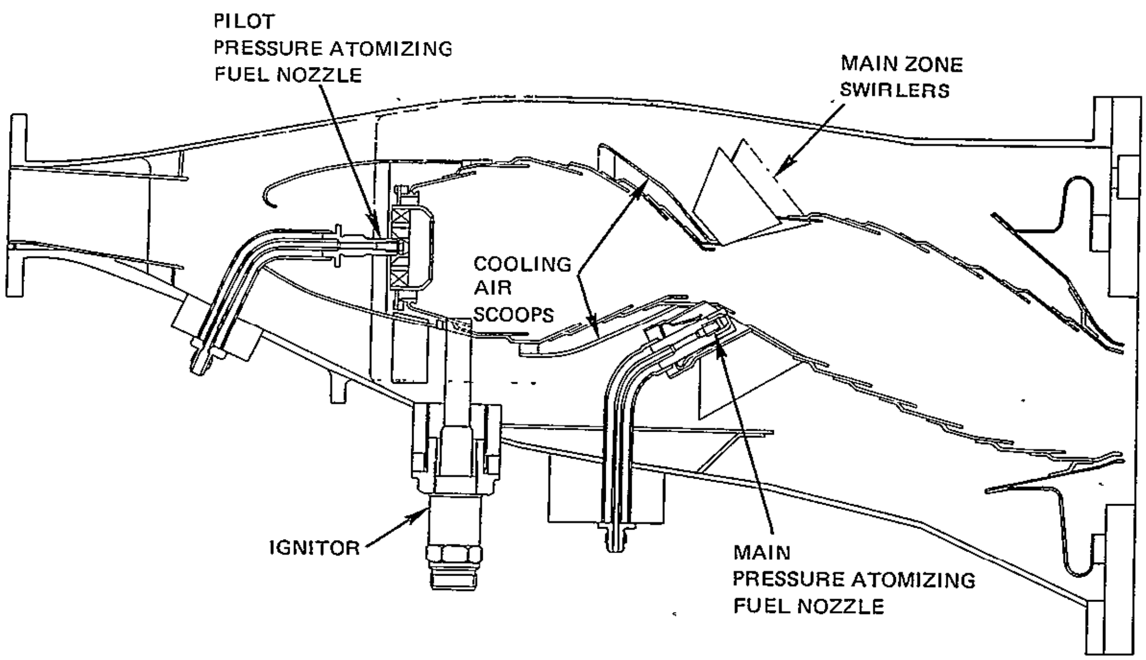


SECTION VIEW OF HYBRID COMBUSTOR

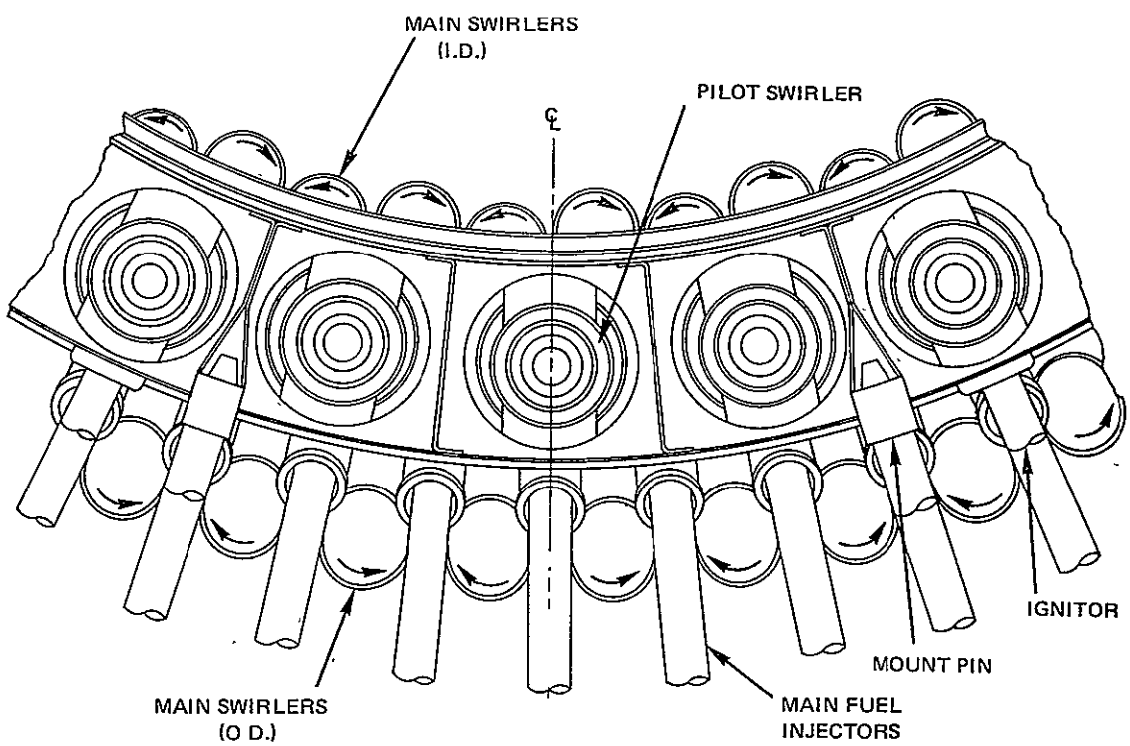


VIEW OF HYBRID COMBUSTOR FRONT END LOOKING DOWNSTREAM

Figure 1 Hybrid Combustor Concept



SECTION VIEW OF VORBIX COMBUSTOR



VIEW OF VORBIX COMBUSTOR FRONT END LOOKING DOWNSTREAM

Figure 2 Vorbix Combustor Concept

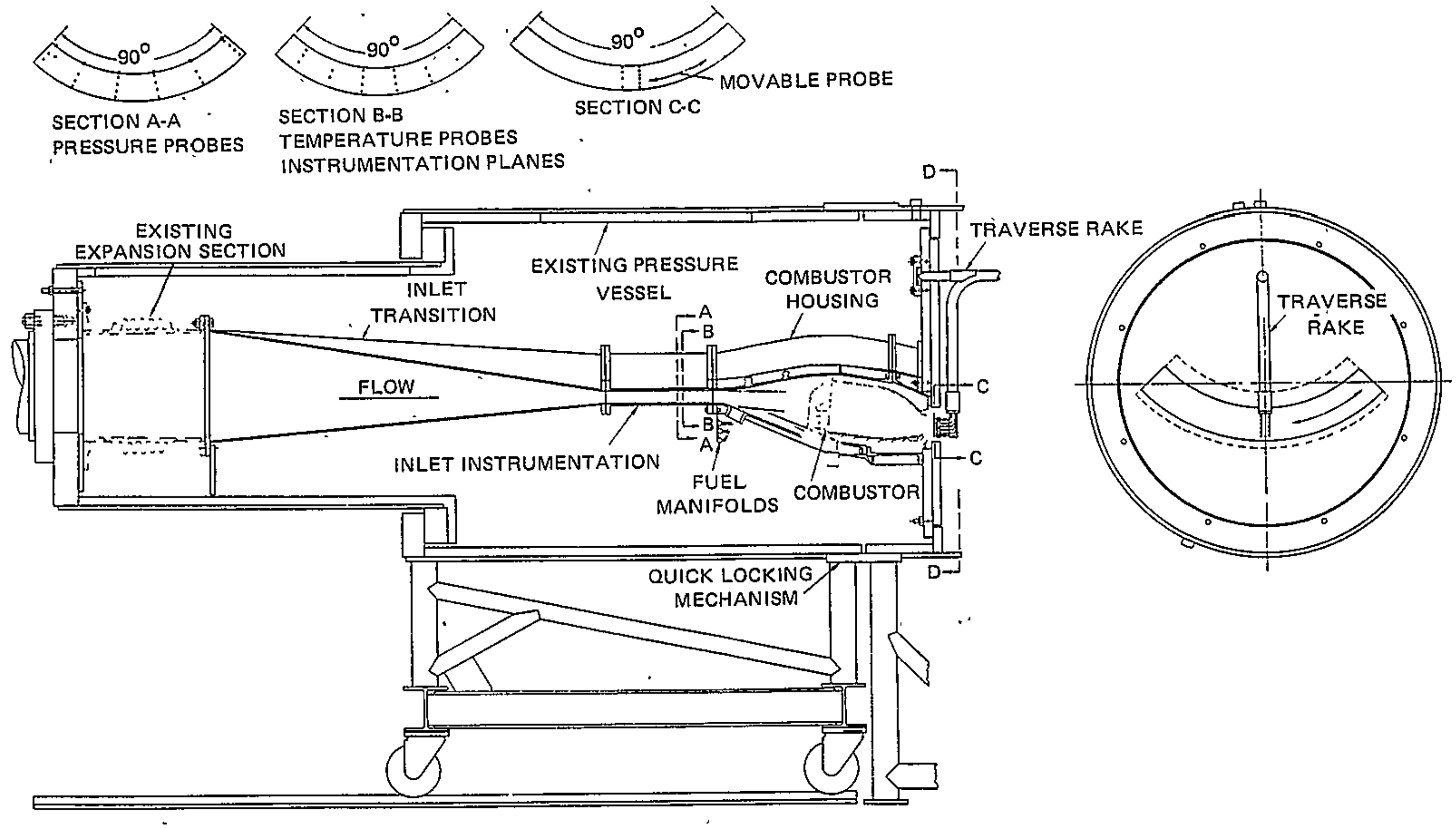


Figure 3 Schematic of Clean Combustor Test Rig in the High Pressure Test Facility

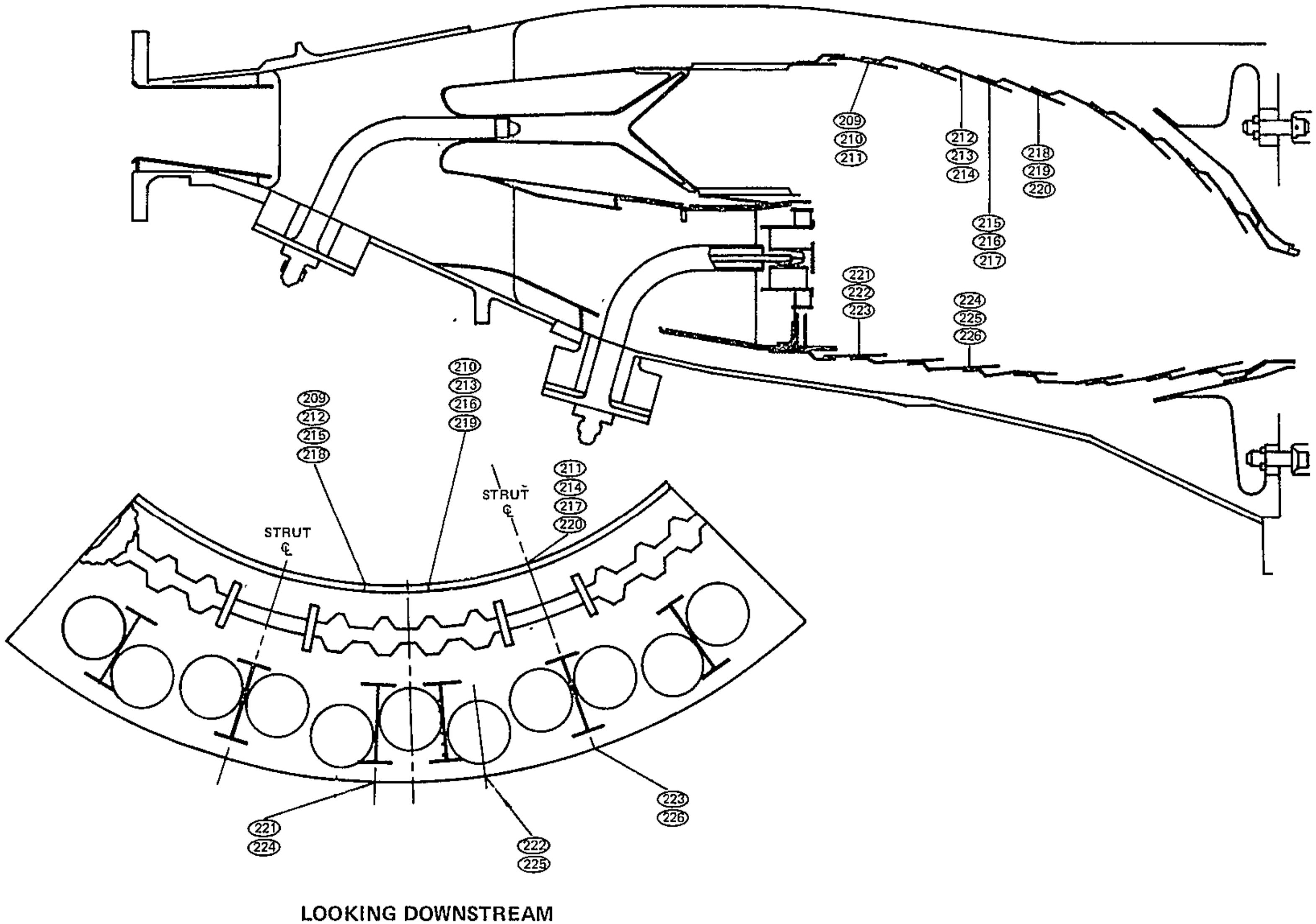


Figure 4 Hybrid Liner Thermocouple Locations

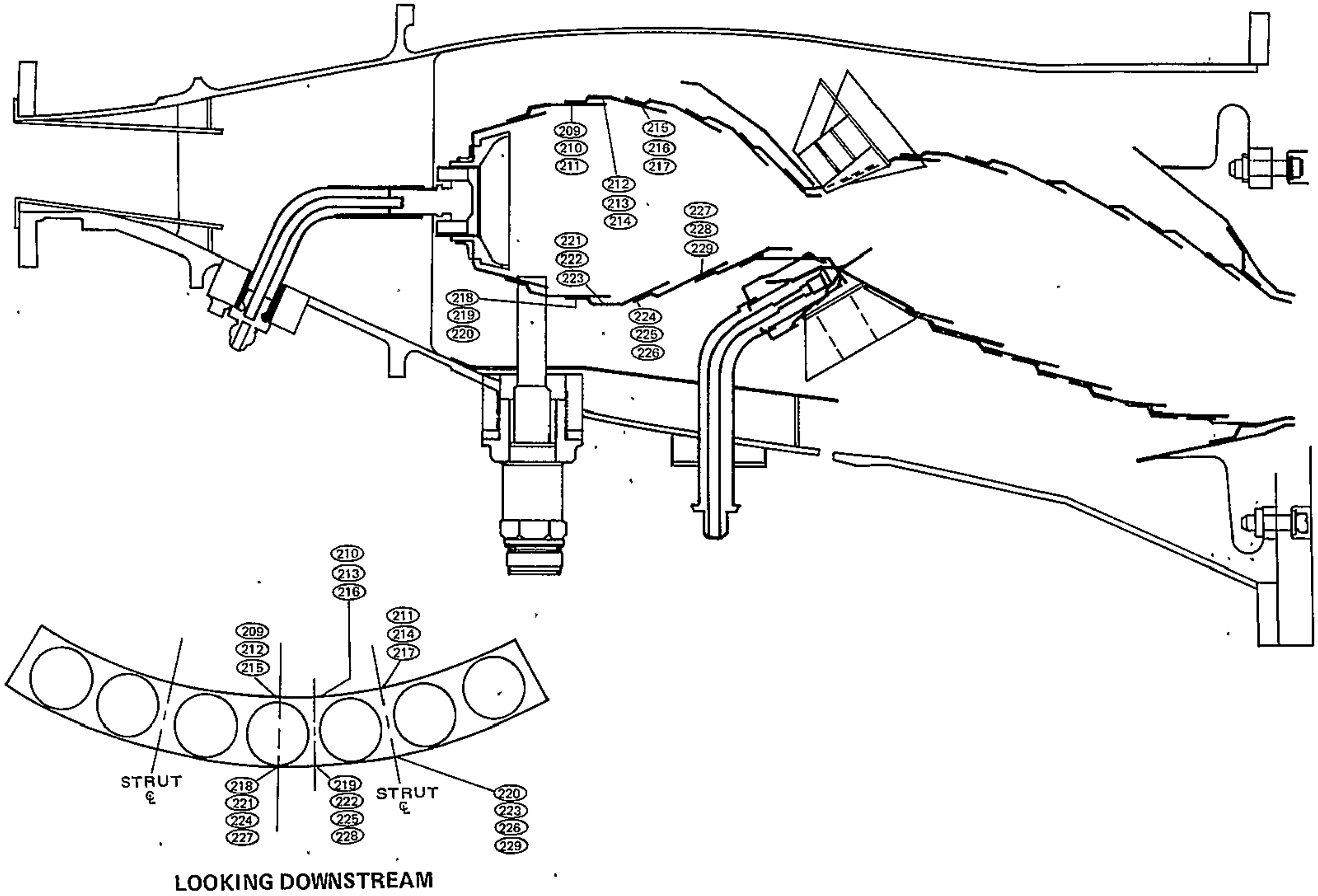


Figure 5. Vorbix Liner Thermocouple Locations

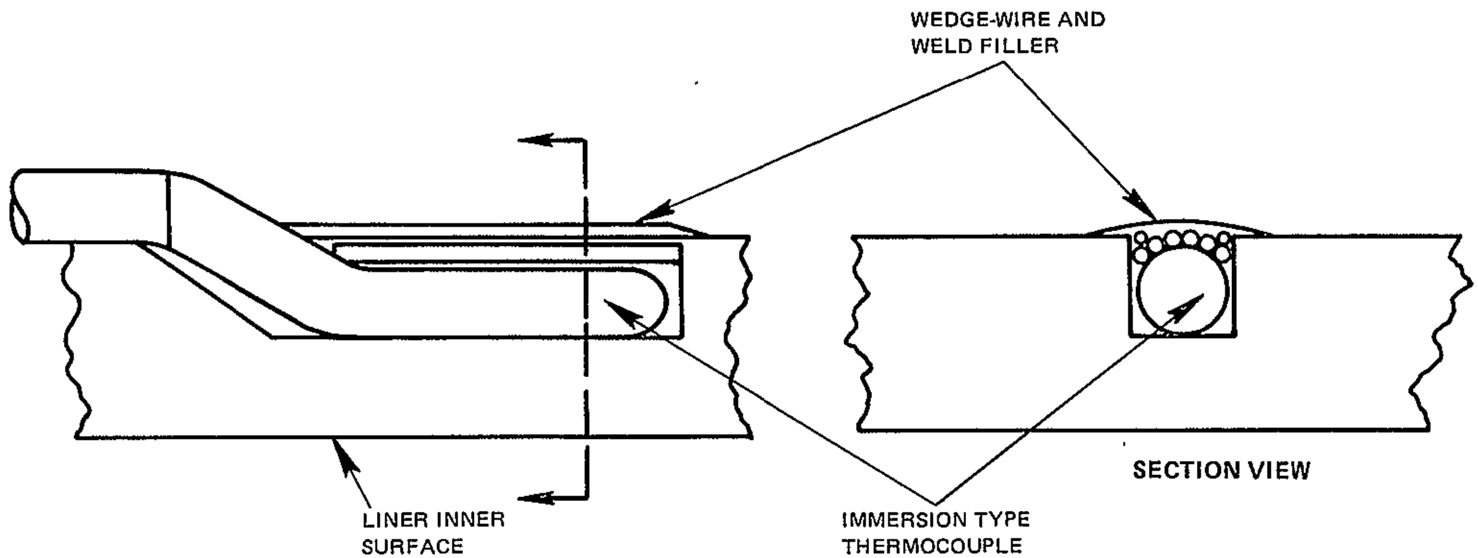


Figure 6 Typical Wedge-Wire Thermocouple Installation

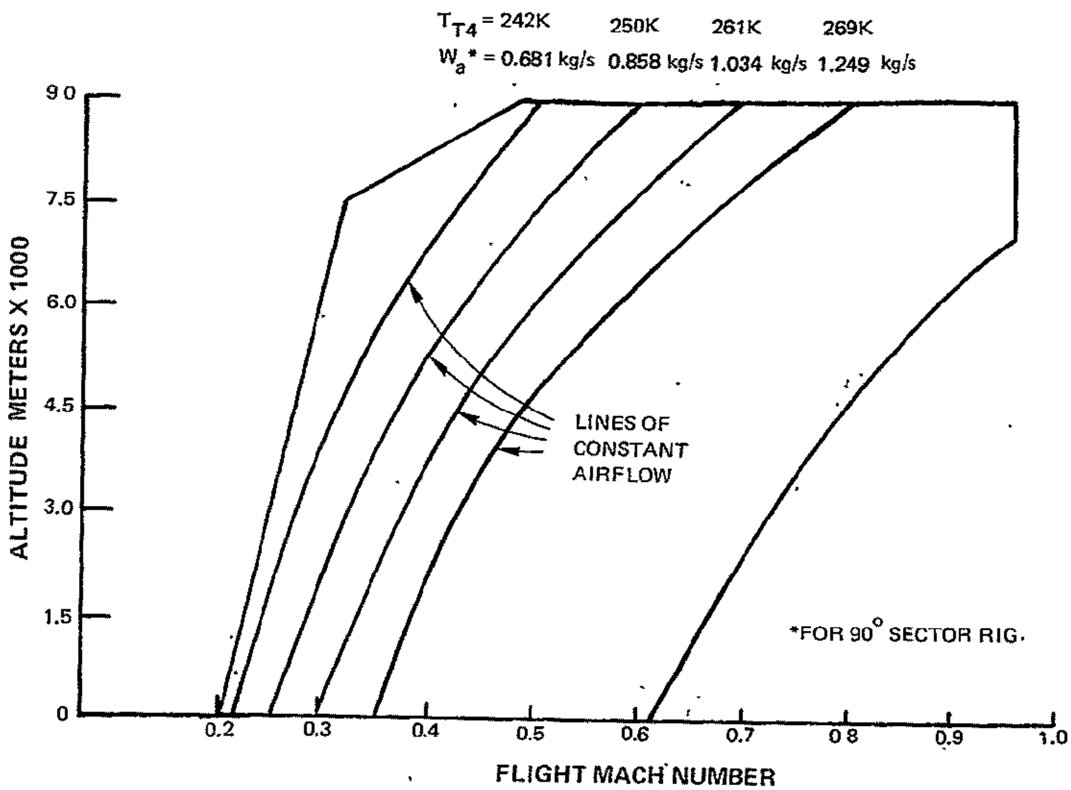


Figure 7 JT9D Relight Envelope

CHAPTER III RESULTS AND DISCUSSION

A. Idle Emission Results

The Idle emission results at the design table Idle condition are presented in Table IV and are plotted versus overall (pilot) fuel-air ratio in Figures 8 through 13).

TABLE IV

IDLE EMISSIONS DATA FOR THE HYBRID AND VORBIX COMBUSTORS CORRECTED TO ENGINE CONDITIONS

HYBRID CONFIGURATION H-6

	Jet A	No. 2 Diesel	No. 2 Home Heat	Jet A + Xylene	Jet A + Naphthalene
Idle (EI)					
NO_x (a, c)	4.3	4.5	4.3	4.5	4.5
CO (b)	10.0	21.0	18.5	12.0	15.0
THC (b, d)	4.4	2.5	3.2	4.7	4.0
Efficiency	99.2	99.2	99.2	99.2	99.2

VORBIX CONFIGURATION S-20

	Jet A	No. 2 Diesel	No. 2 Home Heat	Jet A + Xylene	Jet A + Naphthalene
Idle (EI)					
NO_x (a, c)	3.1	3.2	3.6	3.7	3.4
CO (b)	46.0	54.0	69.0	67.0	46.0
THC (b, d)	6.3	10.6	10.2	6.9	4.2
Efficiency	98.2	97.5	97.2	97.6	98.4

(a) NO_x corrected to engine design table values of inlet pressure, temperature, reference velocity; f/a = 0.0126, corrected to 0.0063 specific humidity.
(b) CO, THC corrected to engine design table inlet pressure.
(c) NO_x expressed as equivalent NO_2.
(d) THC expressed as equivalent CH_4.

Both combustor concepts exhibited increases in NO_x and CO emission indices, relative to the Jet A baseline values, when burning the subject fuels. With reference to Figure 9 for the Hybrid combustor, CO exhibited an increasing trend with both aromatic complexity (Jet A + Xylene versus Jet A + Naphthalene) and increased final boiling point (No. 2 oils versus blends). The increase exceeds 100 percent at the design Idle fuel-air ratio. However, the trend versus hydrogen content was not maintained with the No. 2 oils. The increase in CO emission index for the Vorbix combustor, up to 50 percent at the design point, and the smaller increases

in NO_x for both combustors did not occur systematically with fuel properties. The trend to reduced THC emissions observed for the Hybrid combustor is attributed to the premix-type pilot zone design employed with this concept. The lack of a systematic response makes it difficult to generalize the Hybrid and Vorbix results with respect to fuel properties. As a less-specific generalization, the test fuels as a class produced emissions in excess of the Jet A baseline in all cases except THC for the Hybrid combustor.

B. Sea Level Take-Off Emission Results

The SLTO emission results are presented in Table V at the design conditions, and are plotted versus overall fuel-air ratio in Figures 14 through 19. Pilot fuel-air ratio, which was held constant for this sequence of tests, is identified in Table V and the figures.

TABLE V

SLTO EMISSIONS DATA FOR THE HYBRID AND VORBIX COMBUSTORS CORRECTED TO ENGINE CONDITIONS

HYBRID CONFIGURATION H-6 (Pilot f/a = 0.0076)

	Jet A	No. 2 Diesel	No. 2 Home Heat	Jet A + Xylene	Jet A + Naphthalene
SLTO (EI)					
NO_x (a, c)	18.3	18.6	20.8	21.3	22.0
CO (b)	5.2	2.4	2.5	3.0	3.0
THC (b, d)	0.4	0.2	0.1	0.2	0.2
Efficiency	99.8	99.9	99.9	99.9	99.9

VORBIX CONFIGURATION S-20 (Pilot f/a = 0.0044)

	Jet A	No. 2 Diesel	No. 2 Home Heat	Jet A + Xylene	Jet A + Naphthalene
SLTO (EI)					
NO_x (a, c)	15.6	15.7	14.7	16.1	14.9
CO (b)	11.0	12.1	5.8	8.1	11.0
THC (b, d)	0.1	0.1	0.1	0	0.1
Efficiency	99.7	99.7	99.9	99.8	99.7

(a) NO_x corrected to engine design table values of inlet pressure, temperature, reference velocity; f/a = 0.0227; corrected to 0.0063 specific humidity.

(b) CO, THC corrected to engine design table inlet pressure.

(c) NO_x expressed as equivalent NO_2.

(d) THC expressed as equivalent CH_4.

Examination of the plotted curves indicates that variation of fuel properties at SLTO did not produce the general increases in gaseous emission levels observed at Idle operating conditions. Only the observed NO_x level for the Hybrid combustor exhibited a significant increase over the Jet A baseline. The maximum increase was approximately 20 percent at the design fuel-air ratio, in a direction which might be attributed to reduced fuel hydrogen content. CO and THC emissions for both combustors were at or below the Jet A baseline values, indicating no impact on high power combustion efficiency for the range of fuel composition investigated. The difference in observed NO_x trend for the Hybrid and Vorbix combustors is possibly due to differences in main zone fuel preparation technique. Fuel is injected and partially premixed at compressor discharge conditions in the Hybrid, while main fuel is injected directly into the heated pilot exhaust flow in the Vorbix. The hot environment and locally fuel-rich mixture conditions in the Vorbix would tend to minimize changes in burning rate and localized peak temperature due to changes in fuel evaporation characteristics. Although there is a small theoretical increase in peak flame temperature with decreasing hydrogen content, this is compensated by a corresponding decrease in heating value for the test fuels.

It was anticipated that NO_x emission levels would be higher for the No. 2 fuels as compared to Jet A, since the nitrogen content in these fuels was significantly higher (42 ppm for No. 2 Diesel and 93 ppm for No. 2 Home Heat versus 5 ppm for Jet A). Since not all fuel properties were held constant, the scatter observed at both Idle and SLTO may be due to other factors not under investigation, such as fuel viscosity or volatility.

The SAE smoke numbers for the Hybrid and Vorbix combustors at SLTO are presented in Figures 20 and 21, respectively. The Hybrid combustor demonstrated very low smoke numbers (less than 5) at rig pressure for all of the fuels tested. Smoke number was below the Jet A baseline at lower fuel-air ratio, increasing to approximately the baseline value at the SLTO design fuel-air ratio. The Vorbix combustor, however, exhibited significant increases in smoke number for the subject fuels. The highest Jet A smoke number was 4 as compared to the smoke number for Jet A + Naphthalene which was 23. Smoke number appears to increase with decreasing hydrogen content, with the Naphthalene blend producing considerably higher smoke levels than the Xylene blend. The relatively low smoke produced by the No. 2 Home Heat fuel indicates that neither hydrogen content alone, nor simple characterization of aromatic content, is sufficient to specify smoke formation tendency. The absence of an increasing smoke trend for the Hybrid combustor suggests that intrinsically low smoke concepts, such as the premix-type Hybrid pilot and main zones, will be more tolerant of fuel composition changes which would tend to increase smoke level in a conventional, direct injection combustor.

Figures 22 and 23 show that the combustor radial exit temperature profiles for both combustor concepts are unaffected by the range of fuel composition investigated.

C. Altitude Stability and Idle Lean Blow Out

Minimum pressure blow out (MPBO) tests were conducted at the altitude simulation test facility to evaluate altitude stability. No. 2 Home Heat oil was selected as the test fuel since, due to its increased final boiling point, it was expected to produce the greatest deterioration

in altitude stability. Results for the Hybrid and Vorbix combustor concepts are presented in Figures 24 and 25, respectively. Vorbix configuration S-22 exhibited no deterioration in MPBO, while the Hybrid combustor demonstrated a significant reduction in MPBO capability. A reduction of 1000 m was noted at the low airflow windmilling curve and a 6000 m deficit was incurred at the highest airflow. It appears that the premix pilot incorporated in the Hybrid concept is much more sensitive to increased final boiling point at simulated altitude conditions than the conventional-type Vorbix pilot. In contrast to the deteriorated altitude stability of the Hybrid concept, the Idle lean blow out data (Table VI) indicate no penalty for the range of fuels tested. Similarly, the Vorbix combustor indicated no Idle stability problems.

TABLE VI

IDLE LEAN BLOW OUT FUEL-AIR RATIOS

	Hybrid	Vorbix
Jet A	0.0063	0.0038
No. 2 Diesel	0.0054	0.0036
No. 2 Home Heat	0.0051	0.0037
Jet A + Xylene	–	0.0039
Jet A + Naphthalene	–	0.0037

D. Combustor Liner Durability

Liner temperature data were acquired for both the Hybrid and Vorbix combustors during the rig Idle and SLTO fuels screening tests. These data were taken for the purpose of identifying potential liner durability problems relatable to fuel composition and physical properties. Temperatures were measured by installing approximately 20 embedded thermocouples at selected locations on the Hybrid and Vorbix combustor liners. Interpretation of the resulting temperature data is difficult, since not all of the thermocouples exhibited similar trends. This is possibly due to a variety of reasons, all relatable to the non-uniform nature of the burning fuel-air mixture in the combustor primary zone. Changes in fuel viscosity, volatility, and chemical composition are all expected to affect the atomization, ignition, and combustion processes. Furthermore, the actual burning equivalence ratio and fuel aromatic content will influence the radiant heat flux emitted to the liner. Since the radiant heat load is very significant at high engine power, the reduced rig pressure level of 6.8 atm could mask potential durability problems associated with high pressure radiation loads.

The above considerations imply that the use of liner maximum temperatures to grade the durability impact of the test fuels could be misleading, since shifting liner hot spots cannot be accurately monitored with a finite number of liner thermocouples. Therefore, it was decided to examine the liner thermocouple data on the basis of an average of all temperature

readings relative to the average baseline readings. The same set of thermocouples was used for all tests of a given combustor configuration. Thermocouples which failed part way through the screening tests were eliminated from consideration.

Average liner temperature data for the Hybrid inner liner (pilot side) and Vorbix pilot zone liners are presented in Figures 26 and 27, respectively, for Idle operation. As can be seen from Figure 26, the Hybrid inner liner thermocouples indicated higher metal temperatures at Idle conditions for all of the subject fuels when compared to Jet A. The Vorbix data indicate some scatter on either side of the Jet A baseline. Vorbix liner temperatures were approximately 200 K higher than the corresponding Hybrid values at the Idle design point and exhibited a much steeper trend with fuel-air ratio. This is assumed to be due to the higher bulk fuel-air ratio of the Vorbix pilot design and less conservative liner cooling. However, the actual liner temperature levels for both combustors remain considerably below the maximum levels achieved at high power operation, so the consequence of any local increases is probably small.

Average liner temperature data for the Hybrid outer liner (main zone side) are presented in Figure 28 for simulated SLTO operation. These data correspond to rig operation at 6.8 atm, and have not been corrected to full engine pressure. As can be seen from Figure 28, only a small amount of scatter was observed in average liner temperature level. Since all of the liner thermocouples were located in the pilot of the Vorbix and the pilot fuel-air ratio was held constant at SLTO, liner temperatures did not vary at simulated take-off conditions with changes in main fuel flow. It cannot be concluded on this basis that the variations in fuel properties and chemical composition investigated in this study pose a threat to liner durability.

E. Endurance Test Results

Endurance tests were run on both the Hybrid and Vorbix combustors with No. 2 Home Heat fuel. The program was conducted in two segments; four hours run at SLTO followed by a visual inspection, and four hours run at Idle, followed by teardown and a full inspection. The SLTO portion of the endurance testing was conducted with pilot fuel-air ratios of 0.0077 and 0.0020 for the Hybrid and Vorbix combustors, respectively.

Results of the Hybrid endurance test at SLTO indicated localized burning and carbon deposits on the pilot flameholder. The flameholder distress and carbon deposition continued during the Idle portion of the program. Pilot flameholder durability has been a problem in the past. However, carbon deposition and local burning of the flameholder were noticeably more severe with the No. 2 Home Heat fuel than with Jet A. Figure 29 shows the pilot flameholder in the Hybrid combustor (configuration H-7) following completion of the endurance testing. Carbon deposits were not apparent anywhere in the main zone.

A slight build up of carbon was noted on the outer liner near the main fuel nozzles following the SLTO portion of the Vorbix endurance test, as shown in Figure 30. Figure 31 shows several large carbon deposits removed from the pilot of the Vorbix combustor following the Idle portion of the endurance test. Although this carbon deposition was located in a region where aspiration from the combustor had occurred, similar deposits were not found following the baseline Jet A test program or the SLTO portion of the endurance testing. The severe carbon deposition encountered in the Vorbix pilot, when compared to the lesser amount deposited in the Hybrid, suggests that a pilot of conventional design is less tolerant to increased fuel carbon content and/or boiling range. This observation parallels the observed smoke characteristics at high power, where the premix-type Hybrid combustor proved insensitive to fuel composition and property changes.

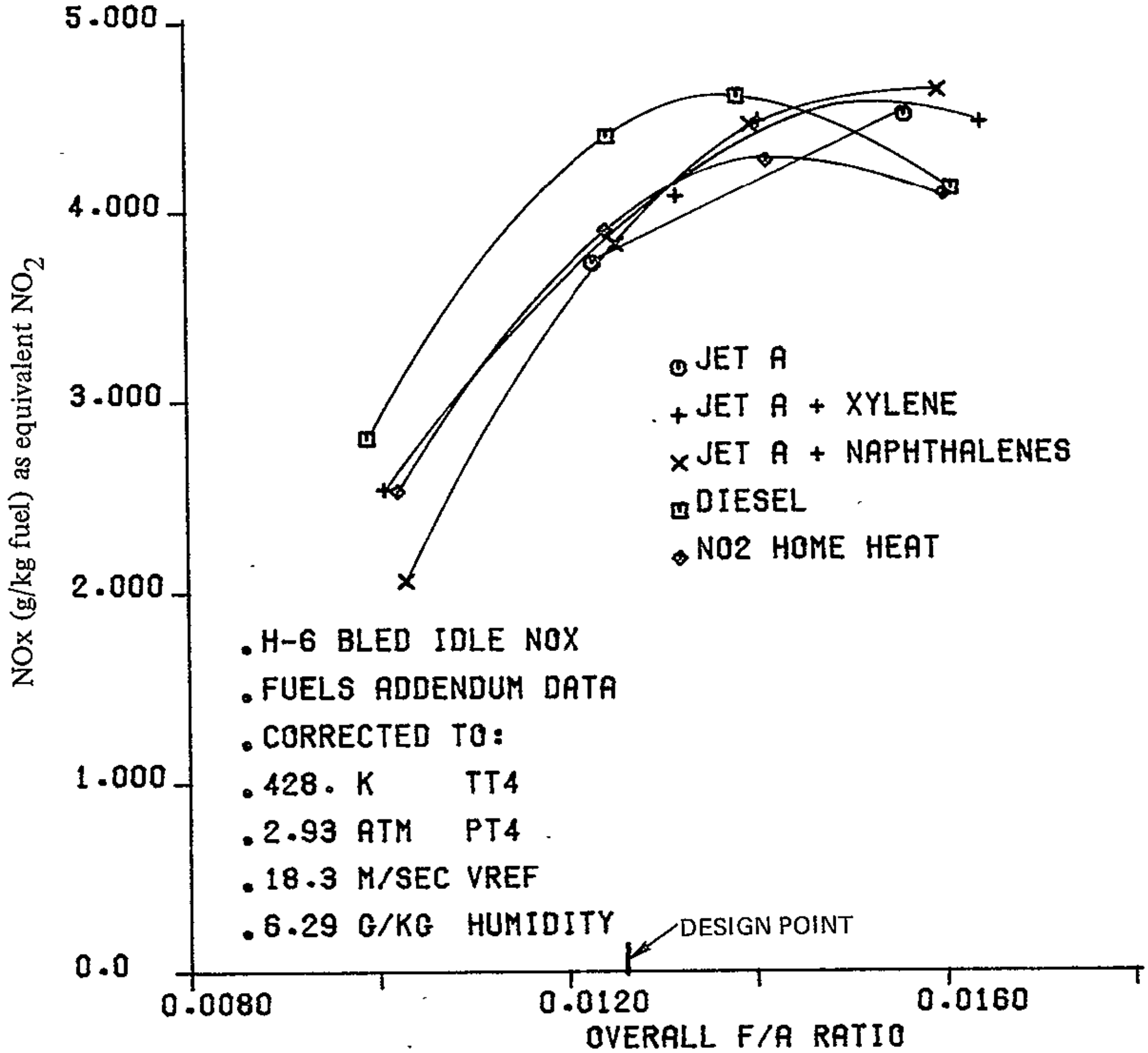


Figure 8 Hybrid Combustor Oxides of Nitrogen Emission Levels as a Function of Fuel-Air Ratio at Idle (Pilot only fueled)

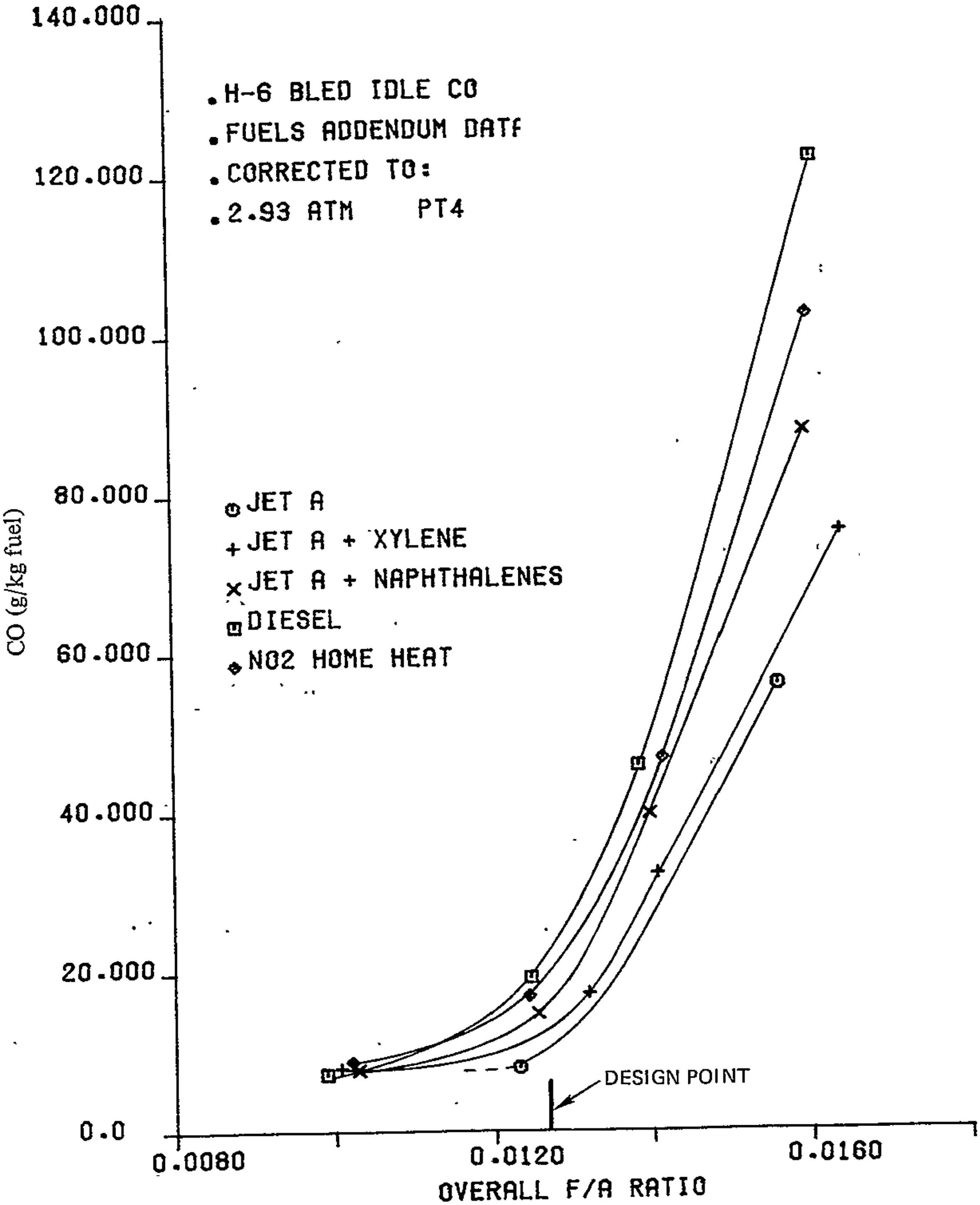


Figure 9 Hybrid Combustor Carbon Monoxide Emission Levels as a Function of Fuel-Air Ratio at Idle (Pilot only fueled)

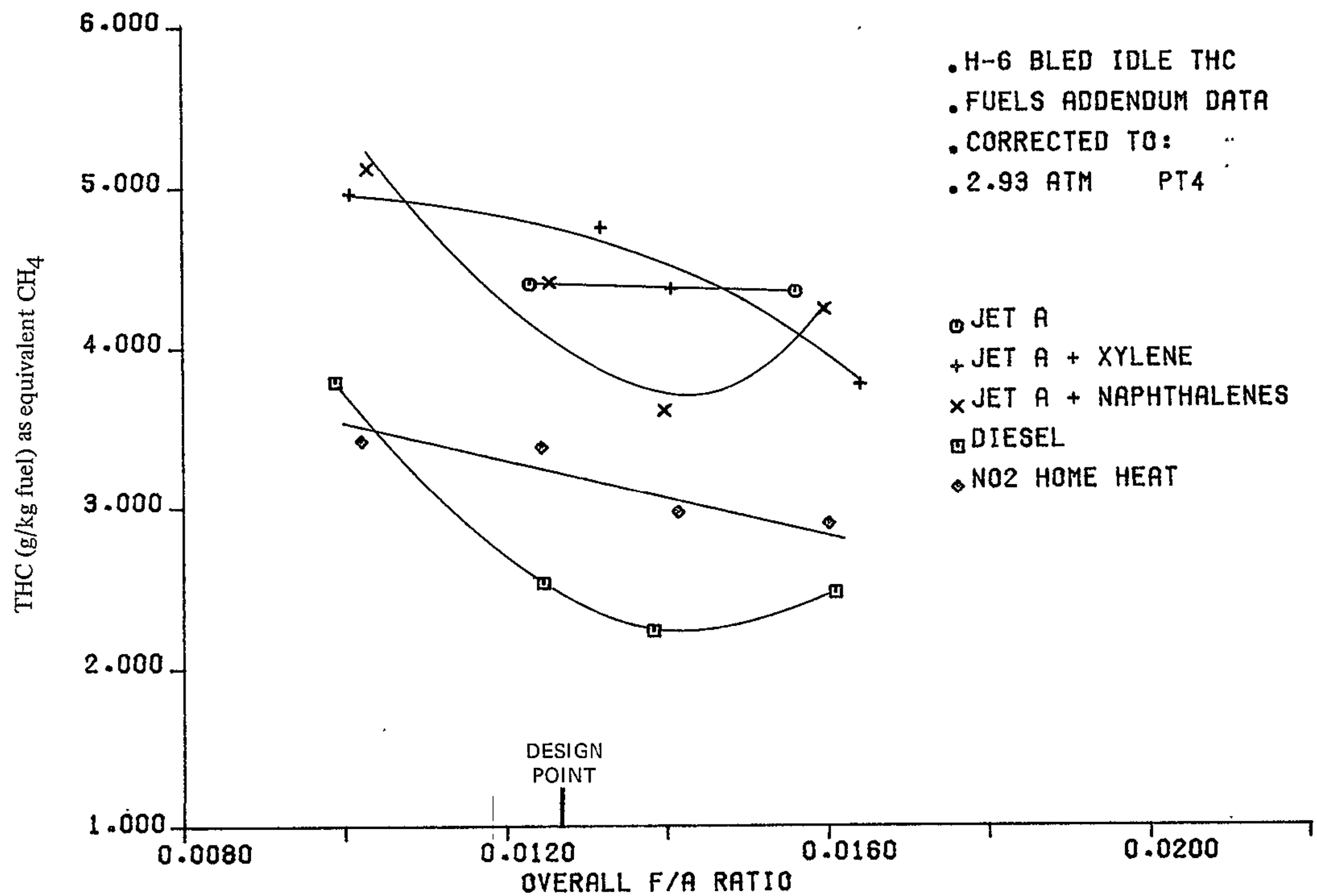


Figure 10 Hybrid Combustor Total Unburned Hydrocarbon Emission Levels as a Function of Fuel-Air Ratio at Idle (Pilot only fueled)

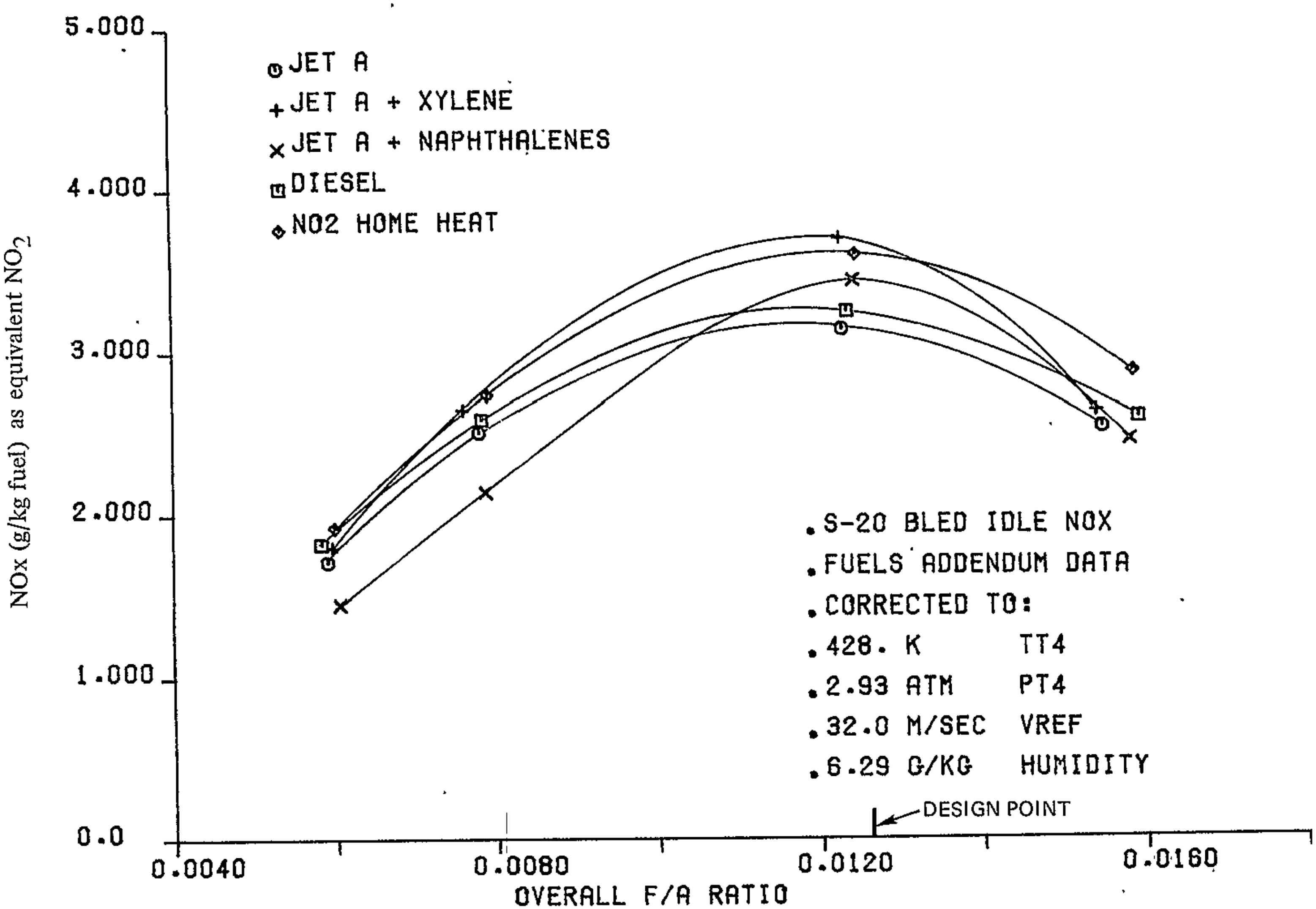


Figure 11 Vorbix Combustor Oxides of Nitrogen Emission Levels as a Function of Fuel-Air Ratio at Idle (Pilot only fueled)

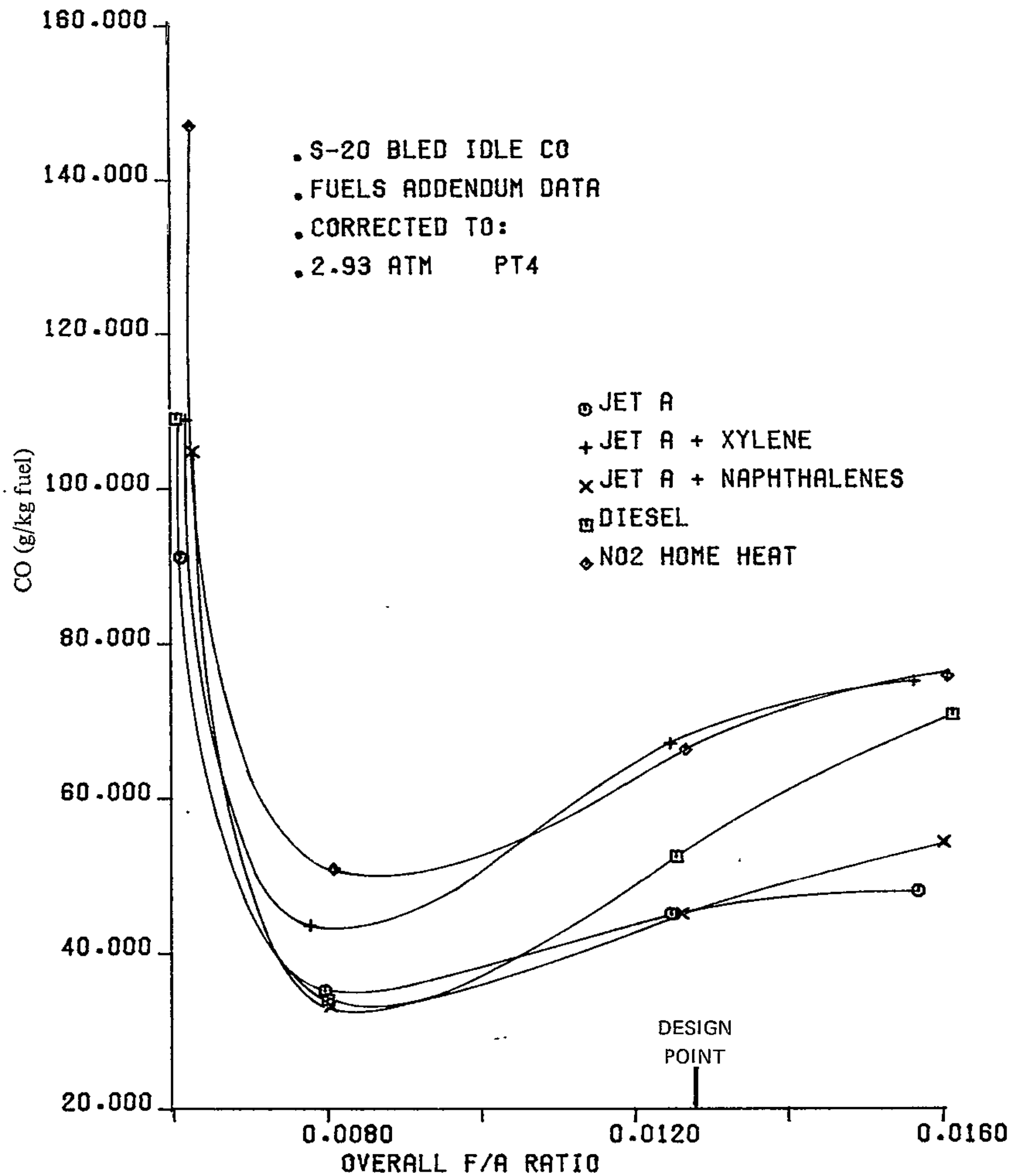


Figure 12 Vorbix Combustor Carbon Monoxide Emission Levels as a Function of Fuel-Air Ratio at Idle (Pilot only fueled)

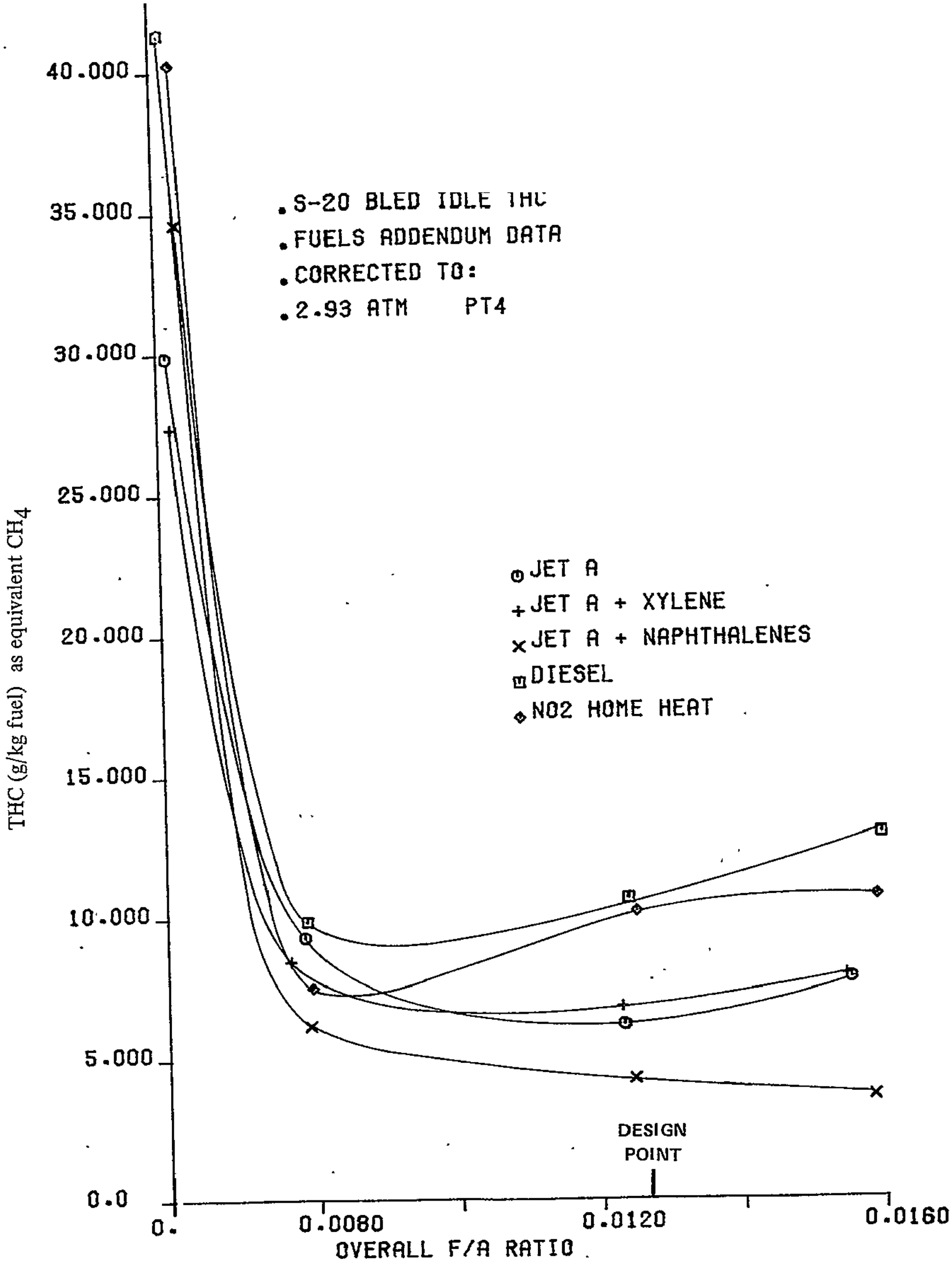


Figure 13 Vorbix Combustor Total Unburned Hydrocarbon Emission Levels as a Function of Fuel-Air Ratio at Idle (Pilot only fueled)

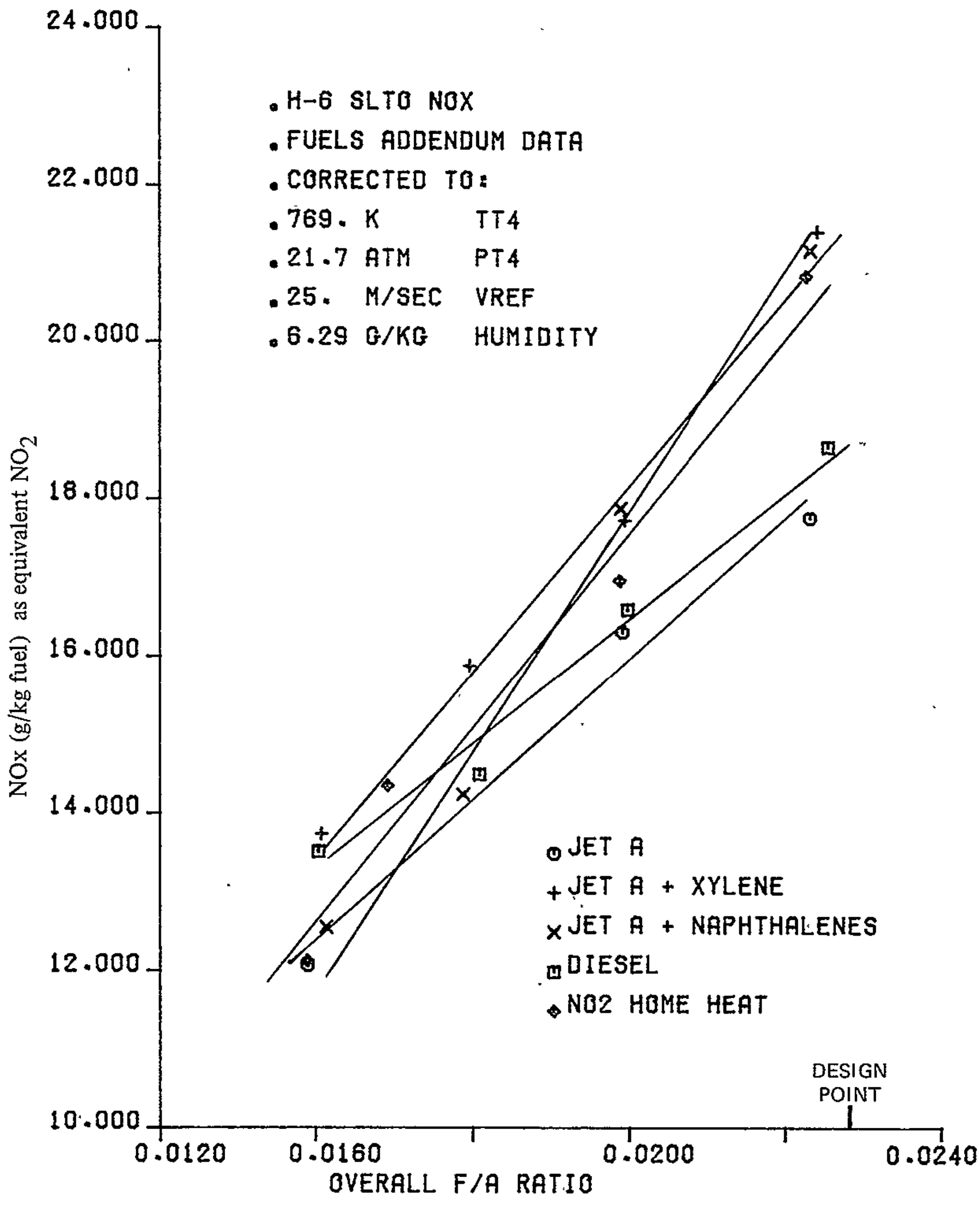


Figure 14 Hybrid Combustor Oxides of Nitrogen Emission Levels as a Function of Fuel-Air Ratio at SLTO (Pilot fuel-air ratio = 0.0076)

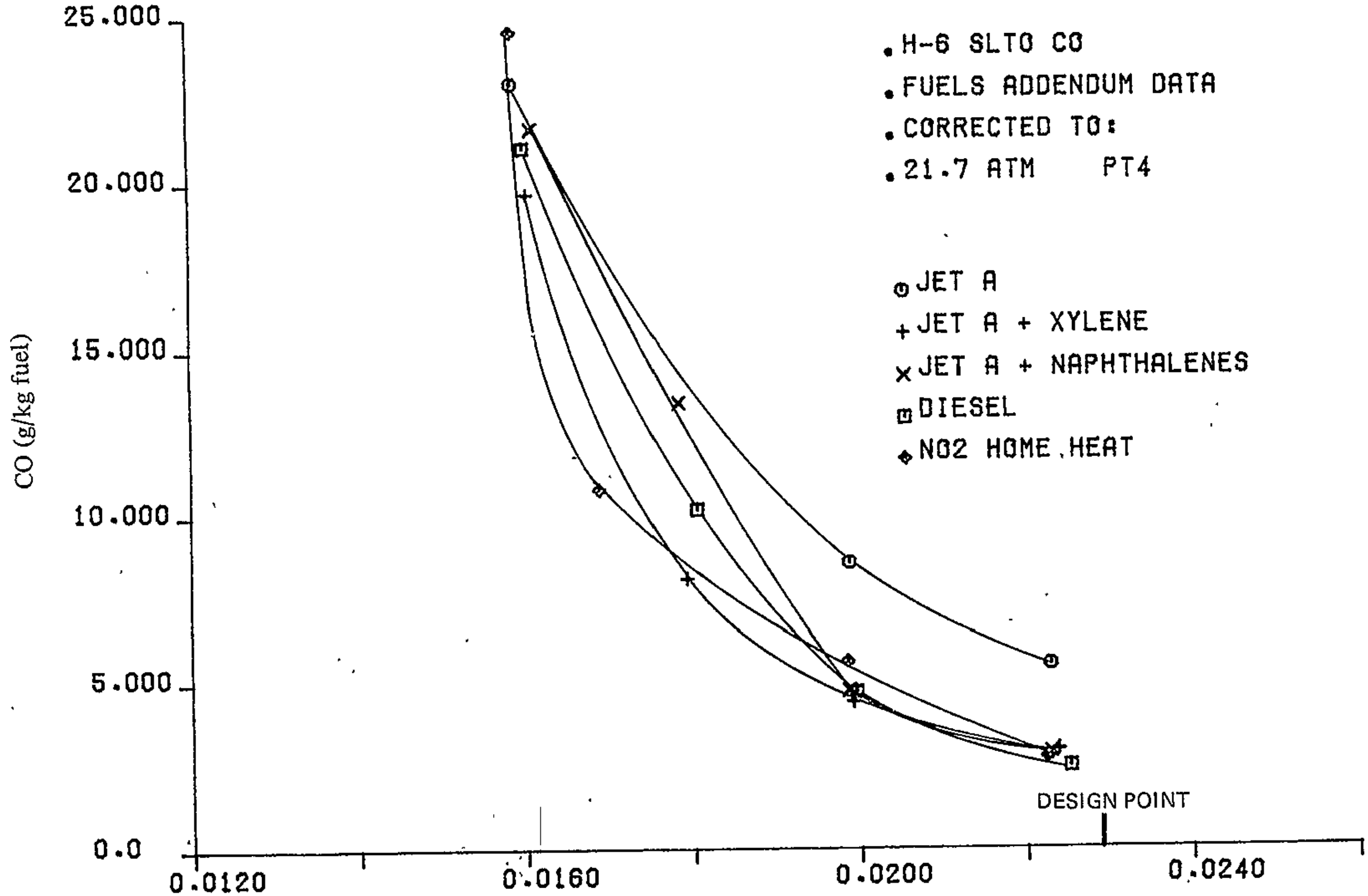


Figure 15 Hybrid Combustor Carbon Monoxide Emission Levels as a Function of Fuel-Air Ratio at SLTO (Pilot fuel-air ratio = 0.0076)

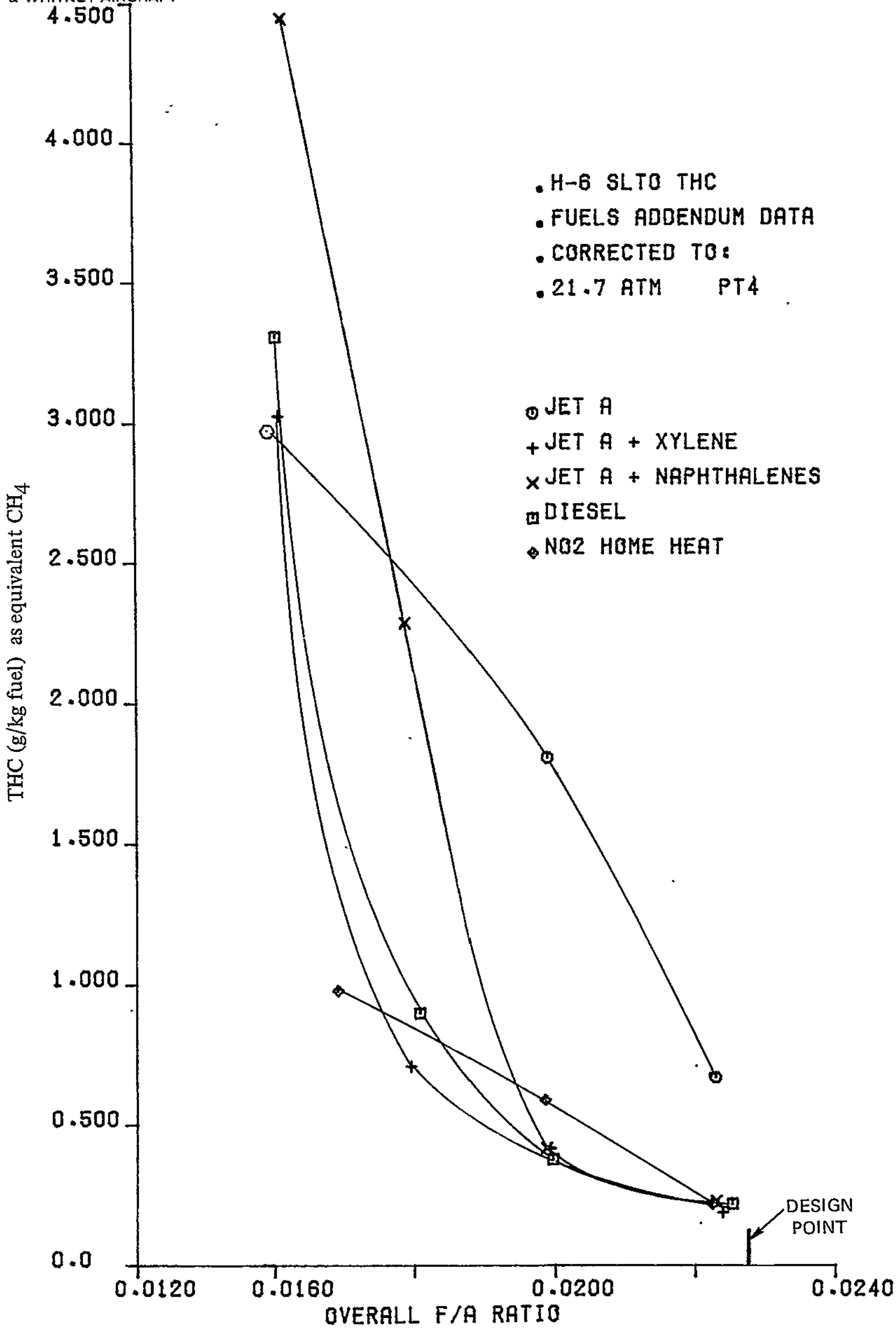


Figure 16 Hybrid Combustor Total Unburned Hydrocarbon Emission Level as a Function of Fuel-Air Ratio at SLTO (Pilot fuel-air ratio = 0.0076)

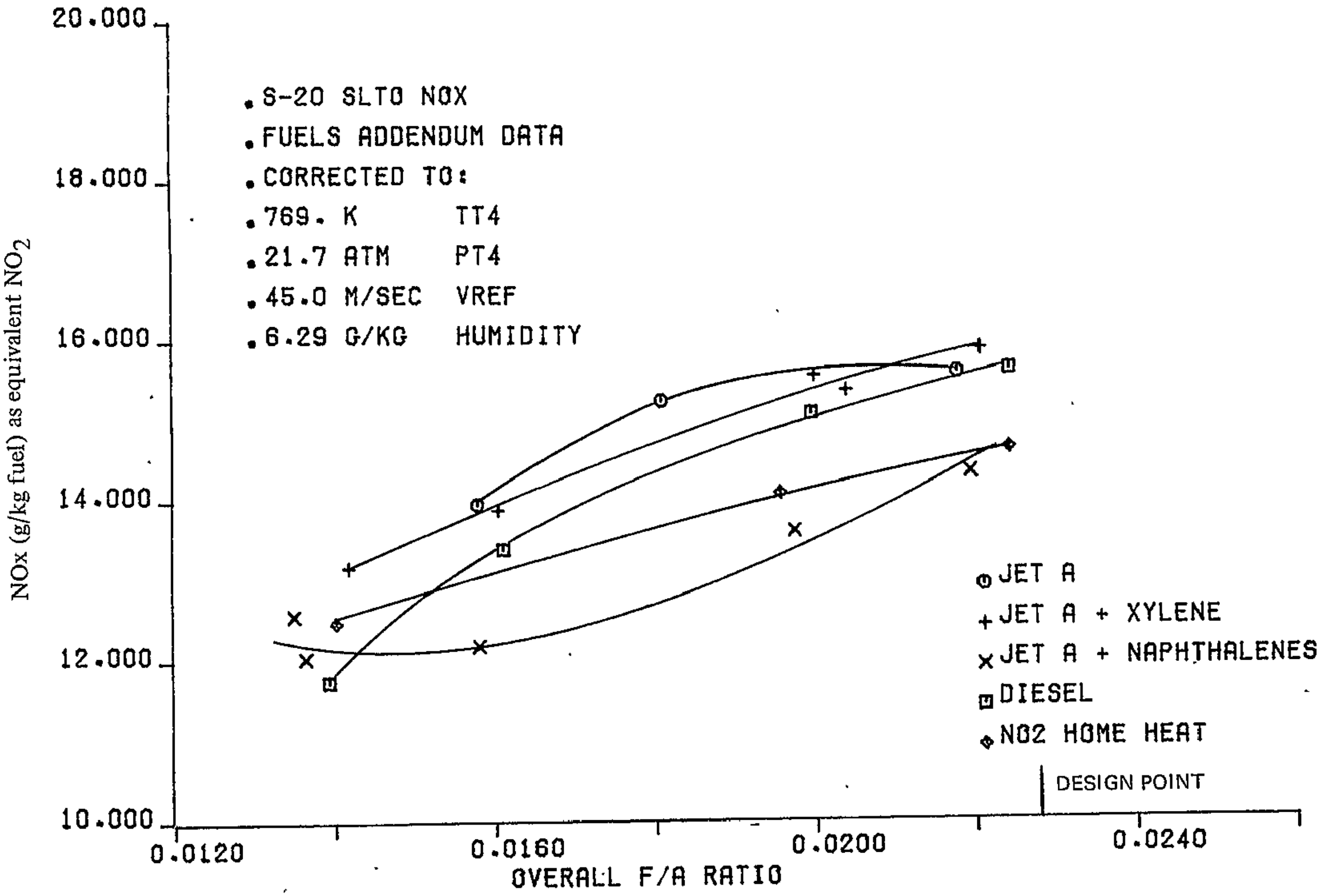


Figure 17 Vorbix Combustor Oxides of Nitrogen Emission Levels as a Function of Fuel-Air Ratio at SLTO (Pilot fuel-air ratio = 0.0044)

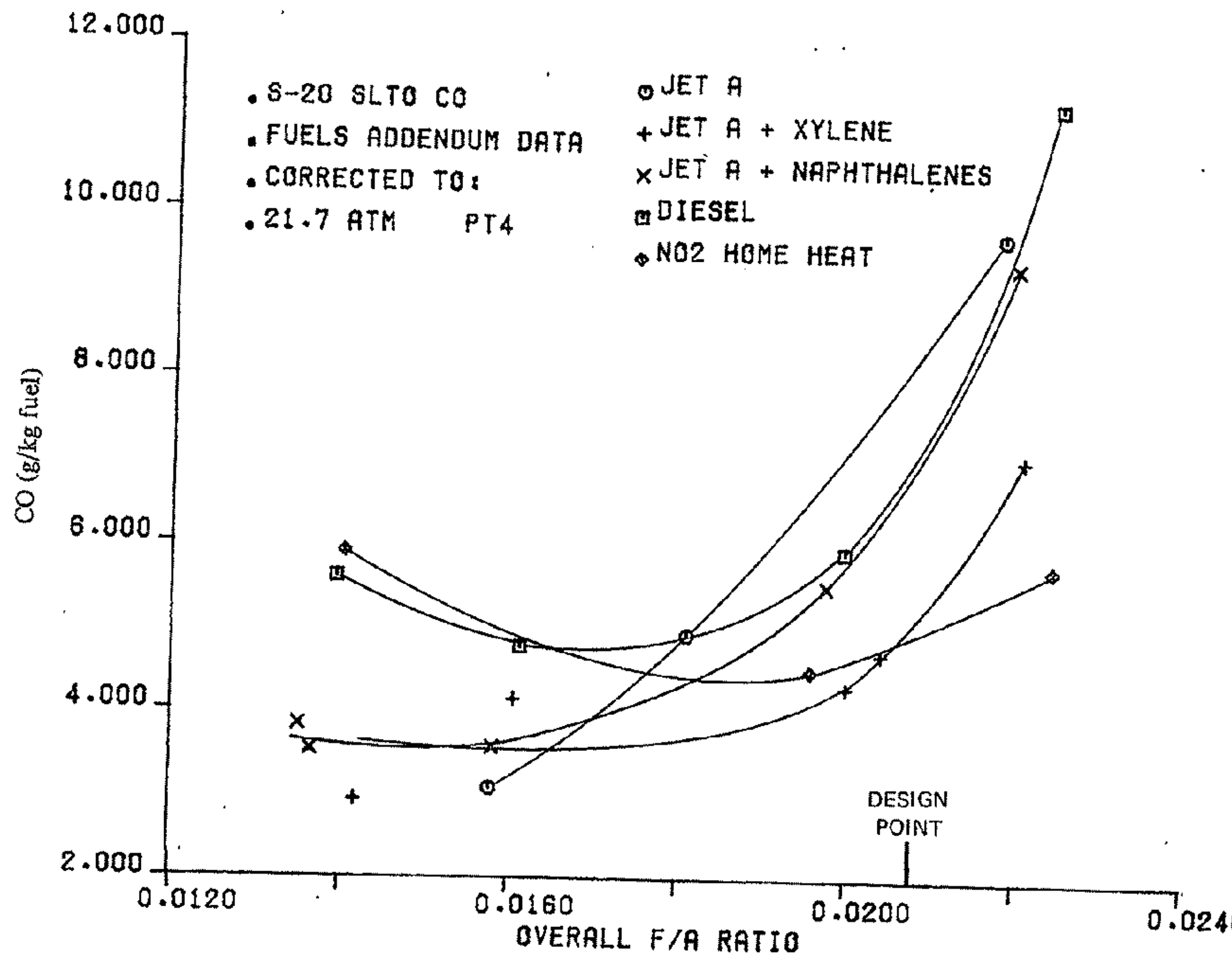


Figure 18 Vorbix Combustor Carbon Monoxide Emission Levels as a Function of Fuel-Air Ratio at SLTO (Pilot fuel-air ratio = 0.0044)

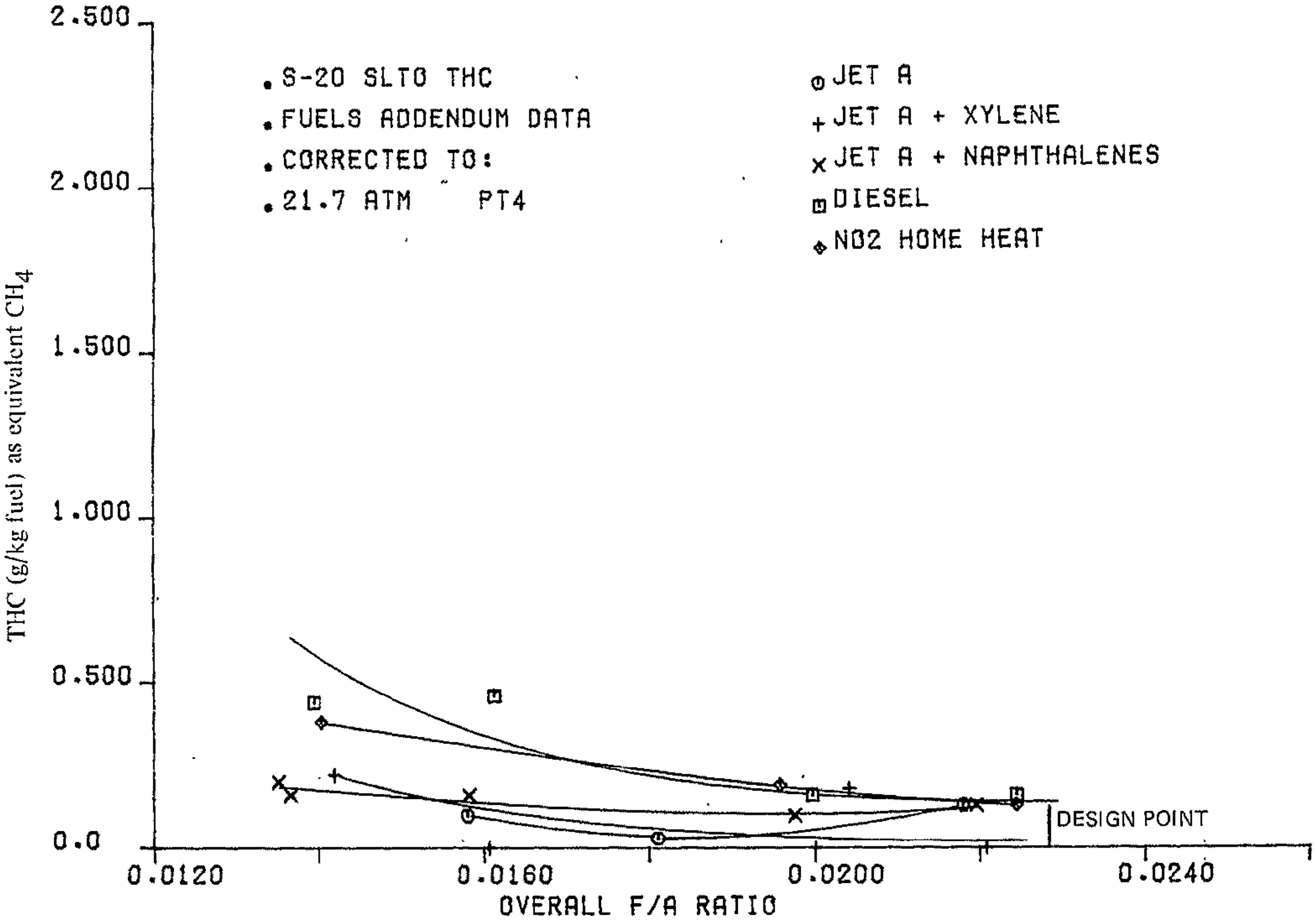


Figure 19 Vorbix Combustor Total Unburned Hydrocarbon Emission Levels as a Function of Fuel-Air Ratio at SLTO (Pilot fuel-air ratio = 0.0044)

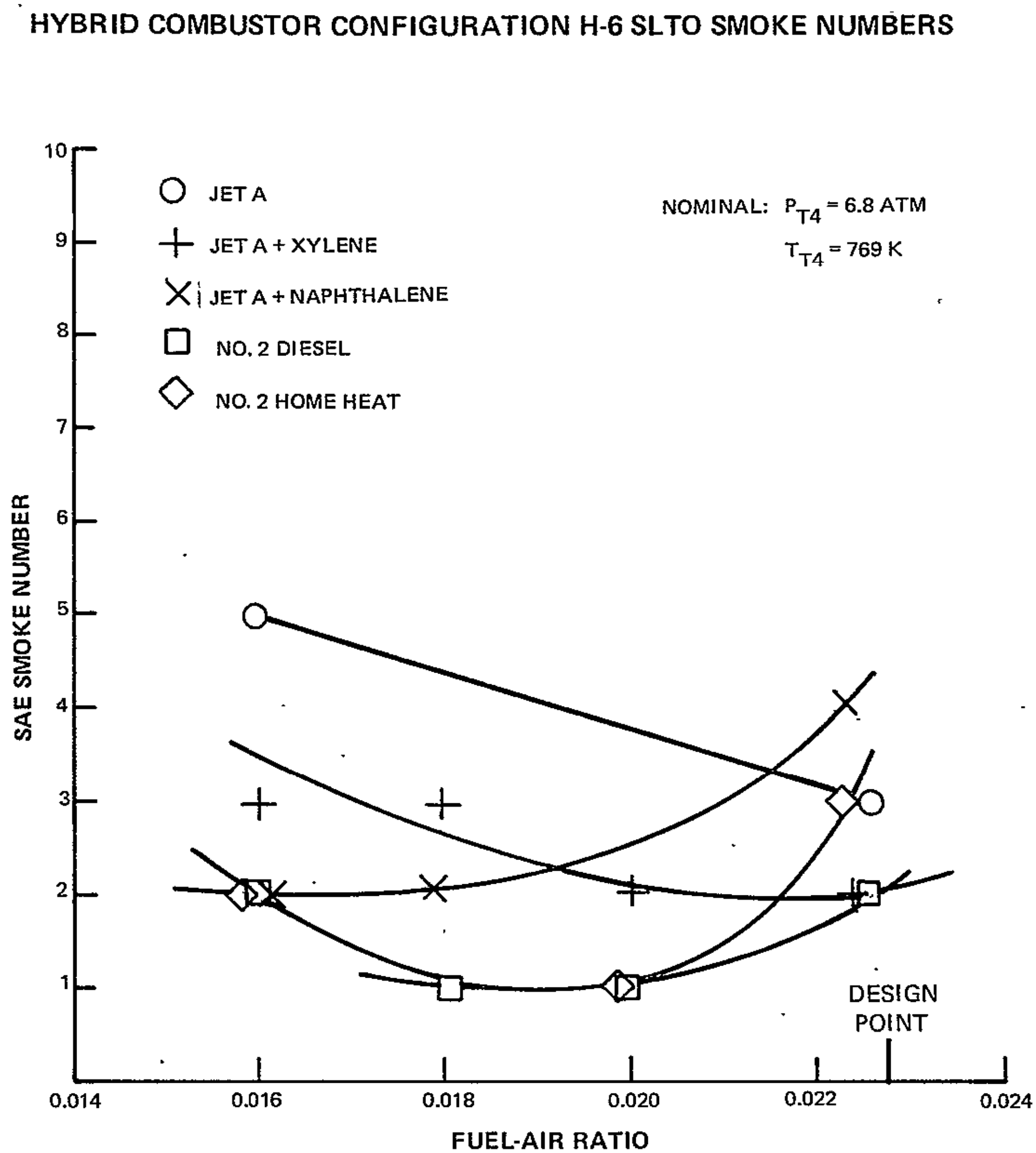


Figure 20 Hybrid SAE Smoke Number as a Function of Fuel-Air Ratio (Pilot fuel-air ratio = 0.0076)

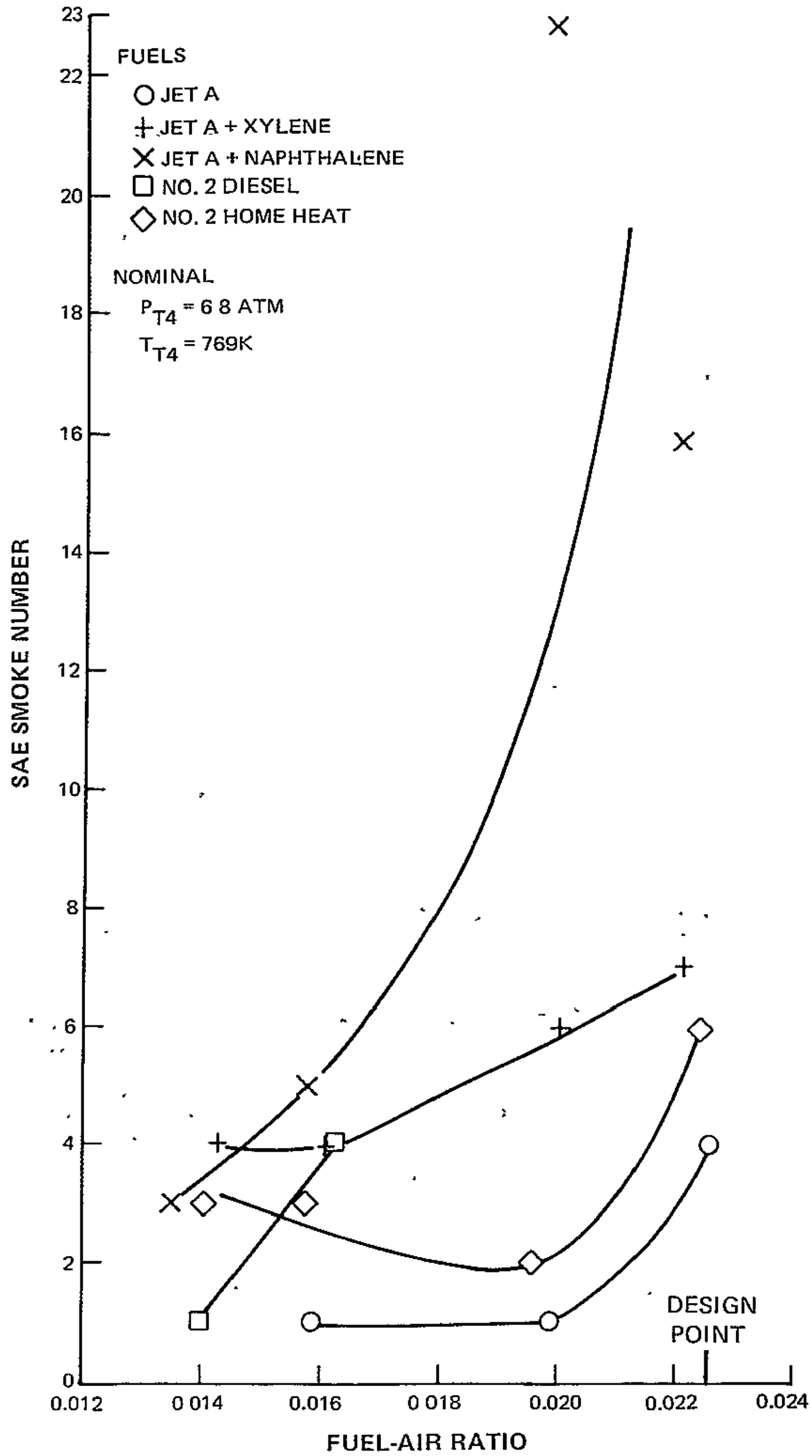


Figure 21 Vorbix SAE Smoke Number as a Function of Fuel-Air Ratio (Pilot fuel-air ratio = 0.0044)

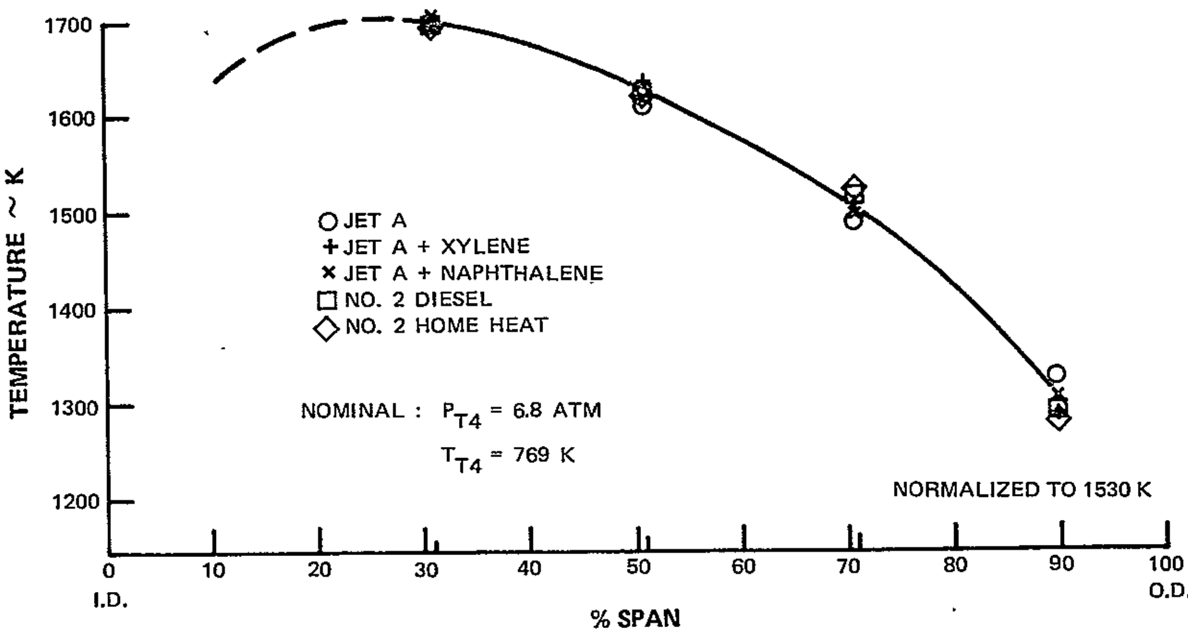


Figure 22 Hybrid Scheme H-6 Combustor Radial Exit Temperature Profile (Pilot fuel-air ratio = 0.0076)

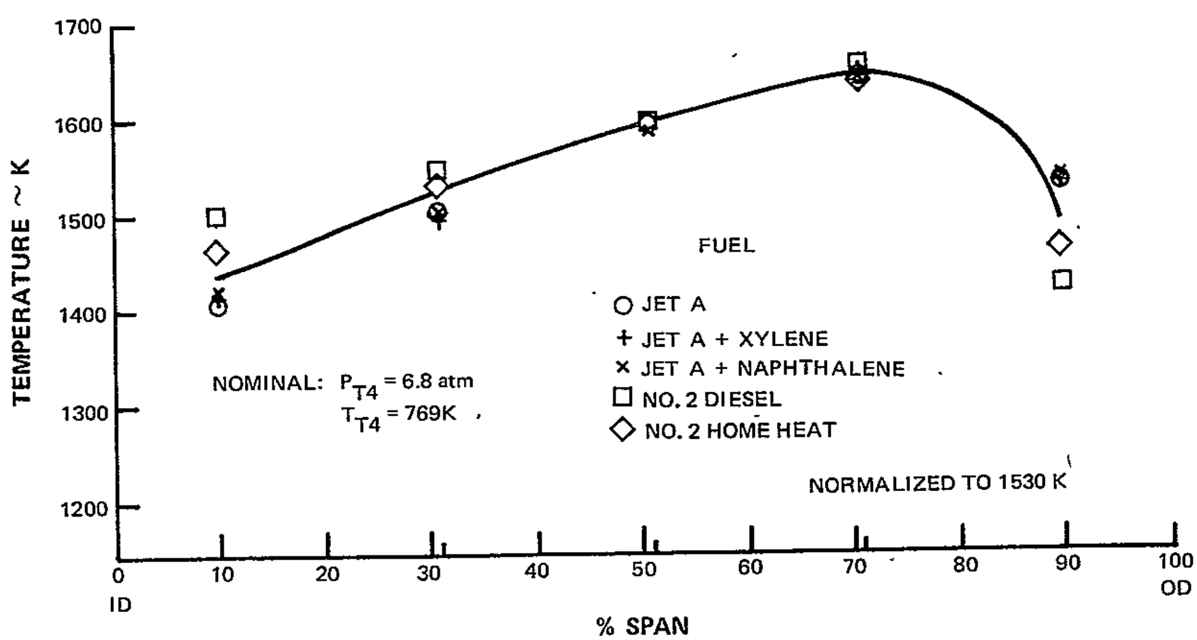


Figure 23 Vorbix Scheme S-20 Combustor Radial Exit Temperature Profile (Pilot fuel-air ratio = 0.0044)

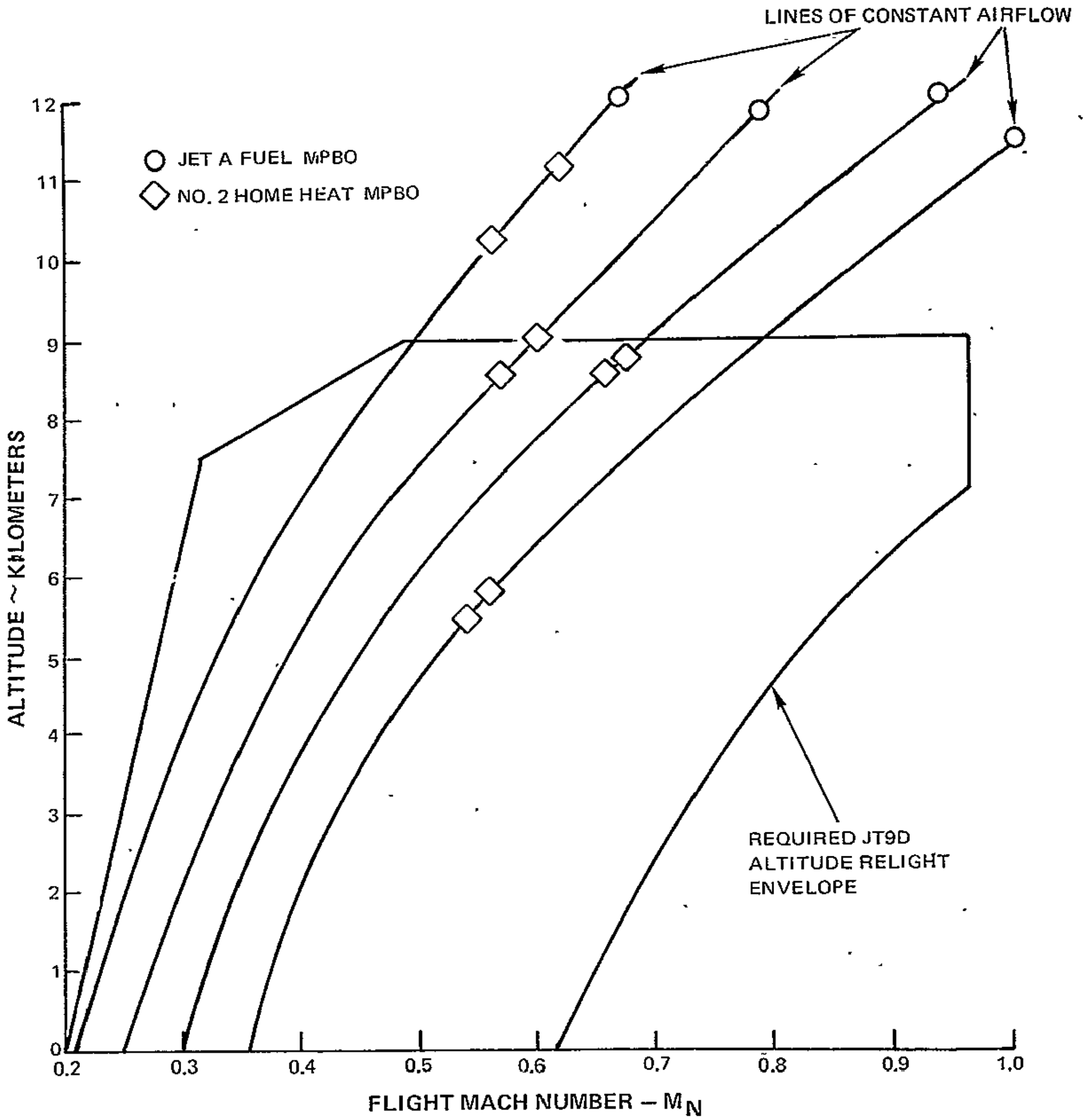


Figure 24 Hybrid Scheme II-6 Minimum Pressure Blow Out Results

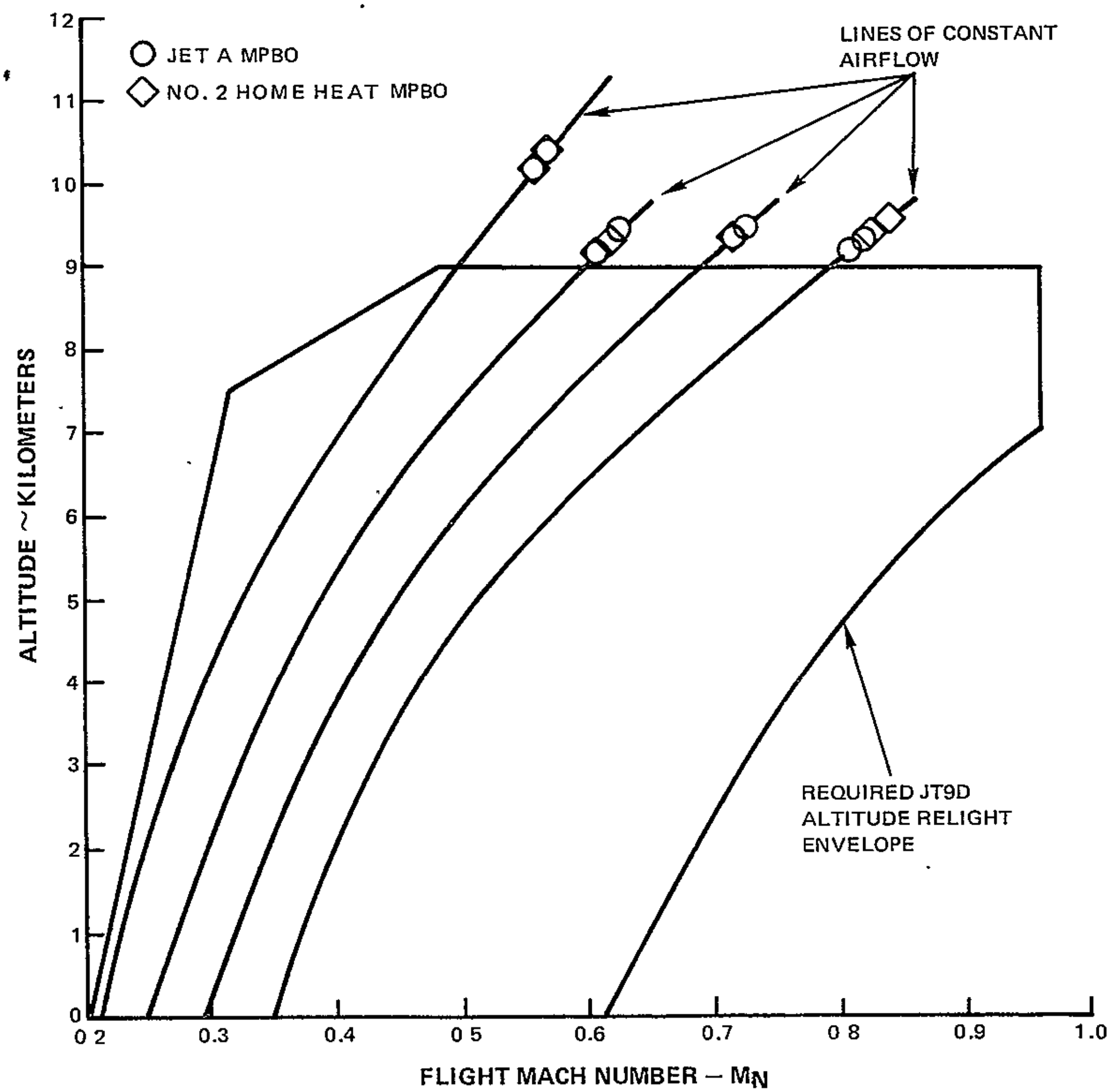


Figure 25 Vorbix Scheme S-20 Minimum Pressure Blow Out Results

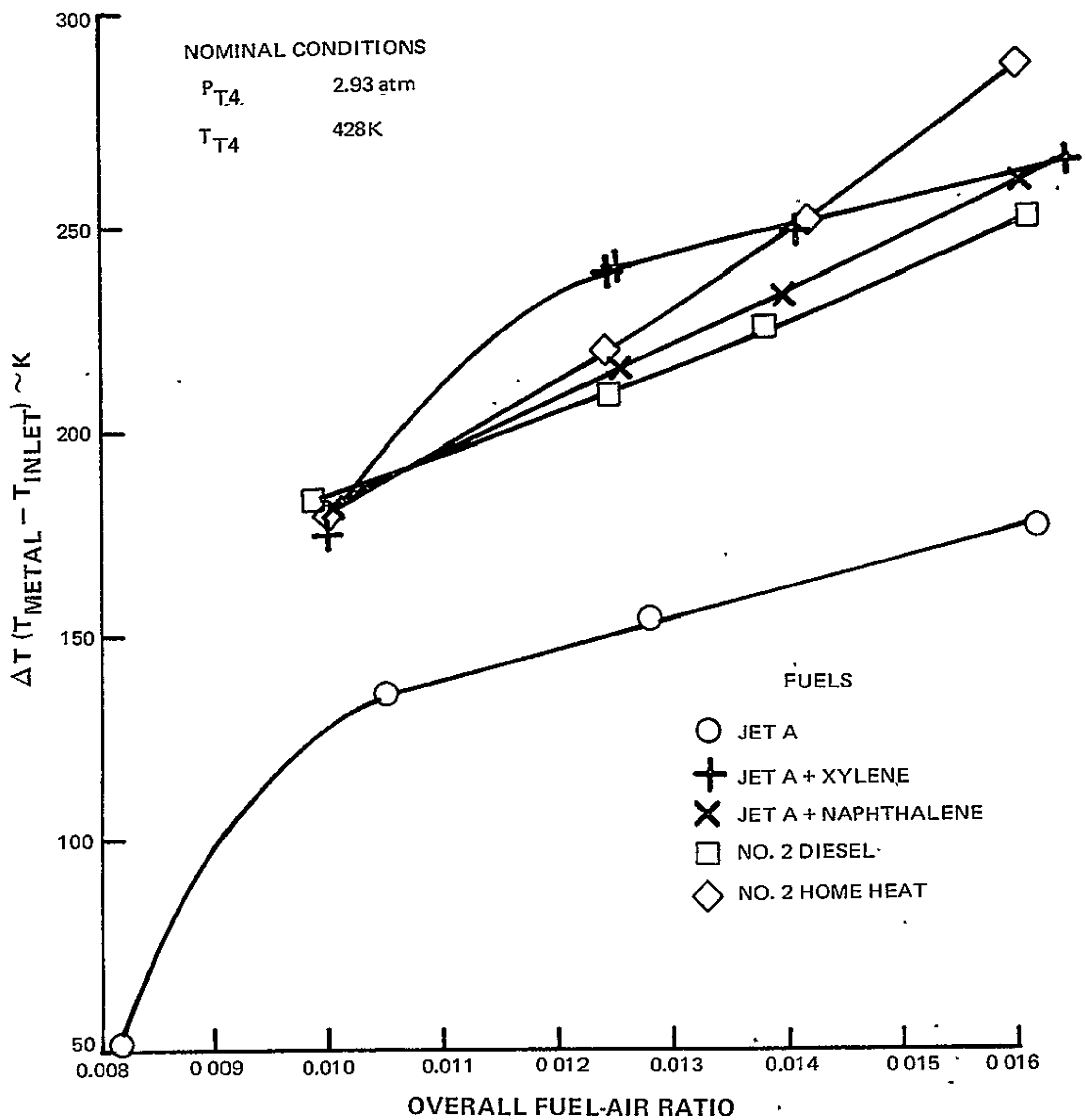


Figure 26 Average Inner Liner Metal Temperature at Idle, Hybrid Configuration H-6 (Pilot only fueled)

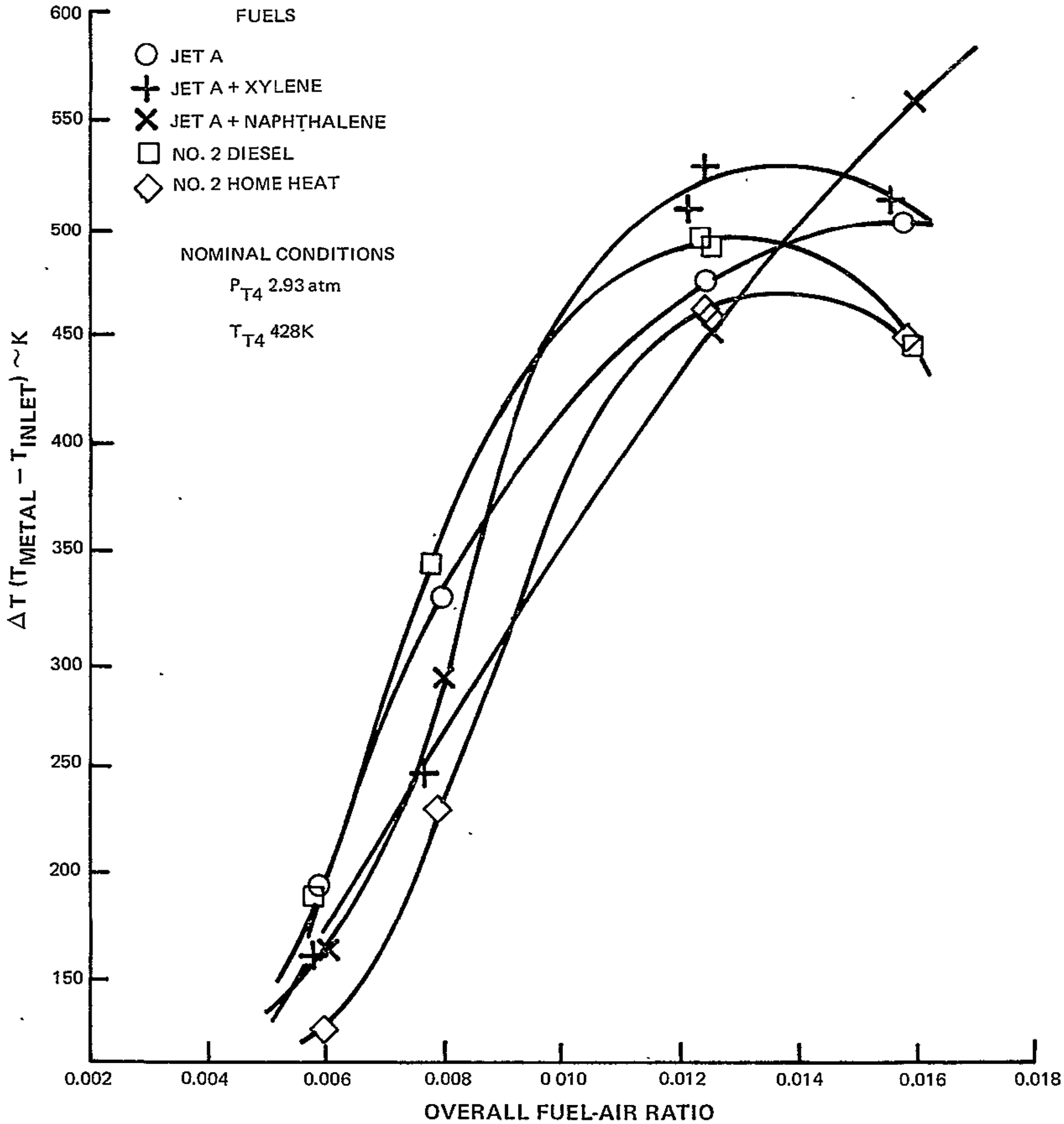


Figure 27 Average Pilot Liner Metal Temperature at Idle, Vorbix Configuration S-20 (Pilot only fueled)

HYBRID COMBUSTOR CONFIGURATION H-6
OUTER LINER METAL TEMPERATURE AT SLTO (AVERAGE)

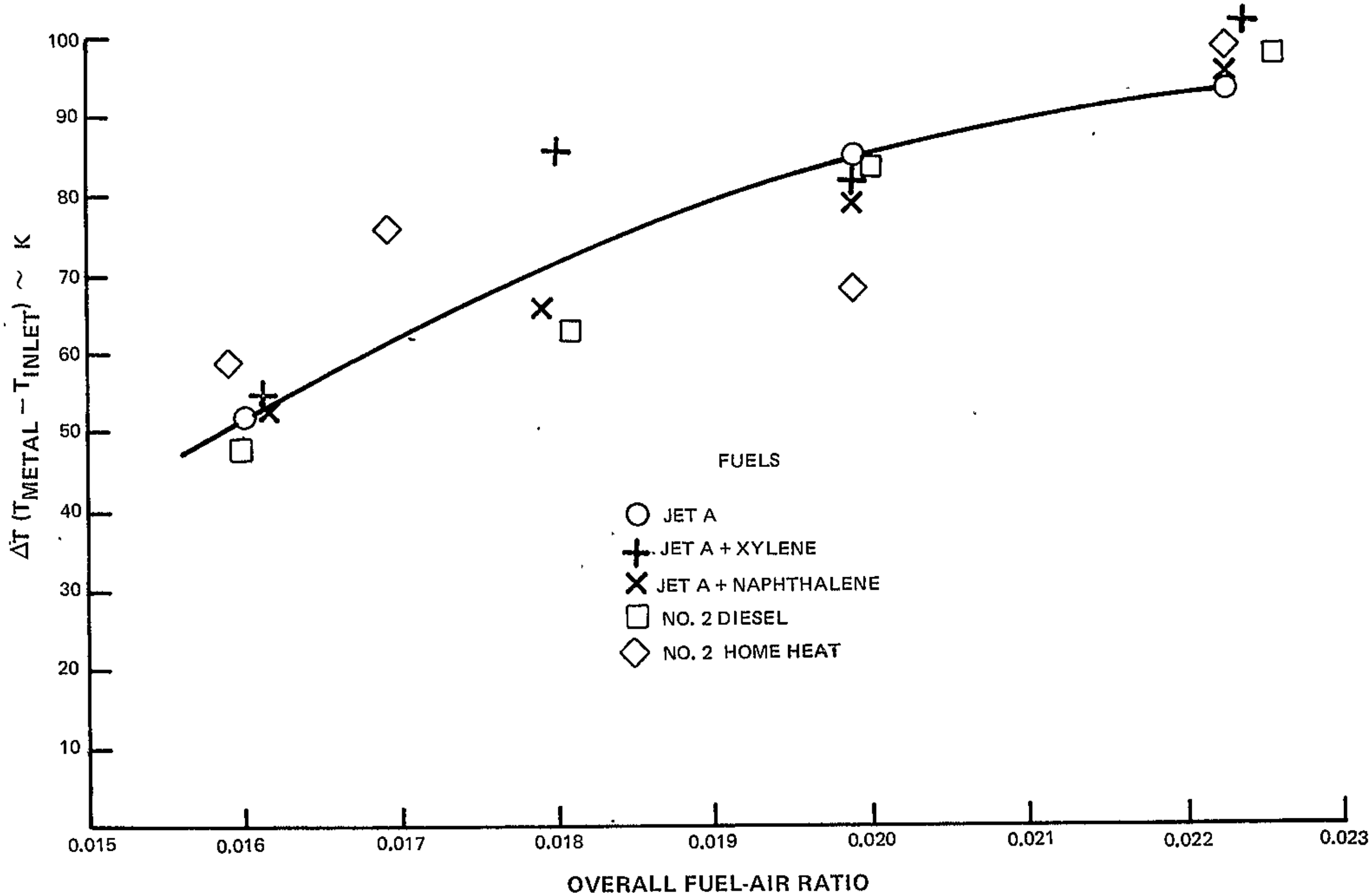


Figure 28 Average Outer Liner Metal Temperature at SLTO, Hybrid Configuration H-6 (Pilot fuel-air ratio = 0.0076)

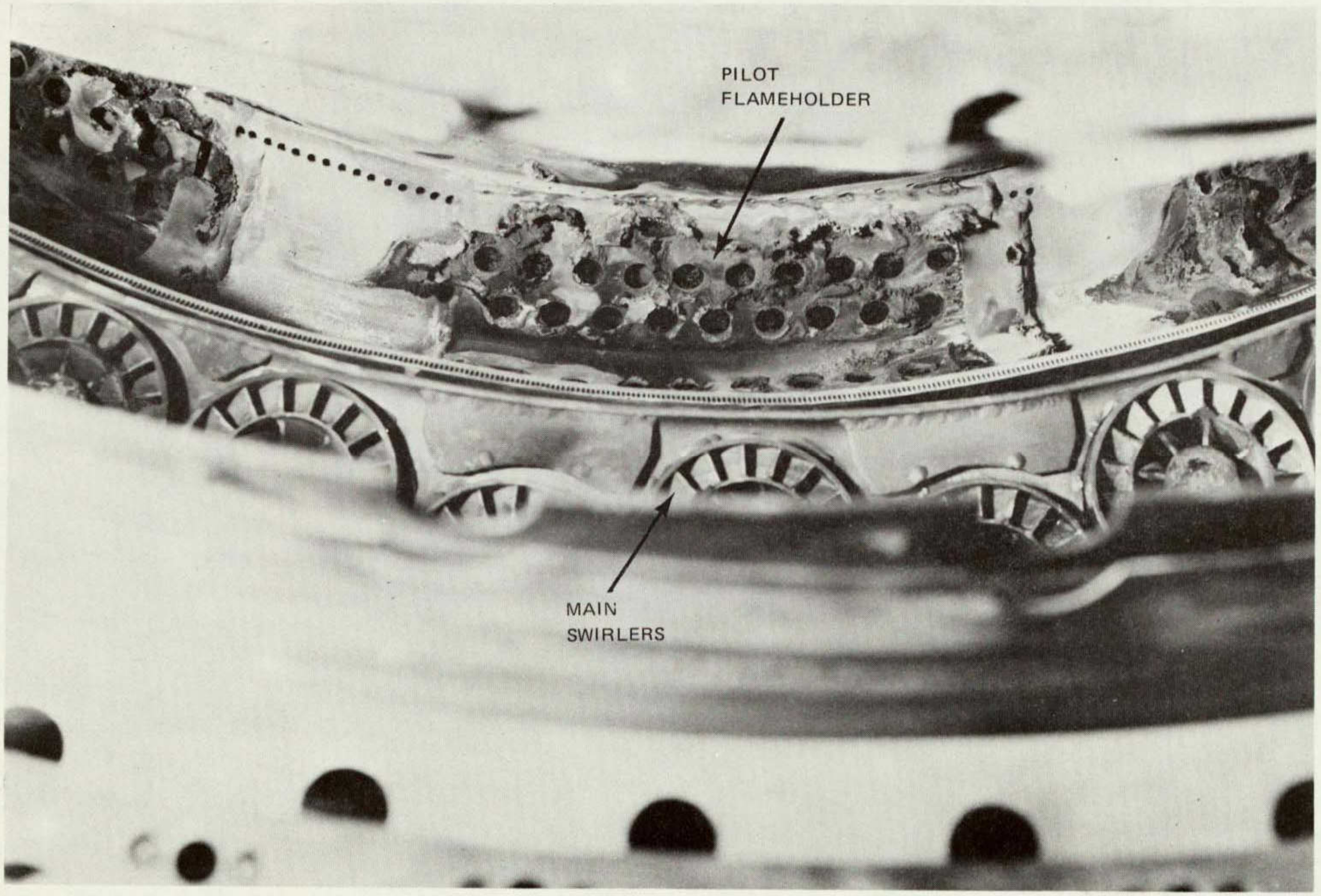


Figure 29 View Looking Upstream, Hybrid Combustor Configuration H-6, Following the Endurance Test on No. 2 Home Heat Fuel

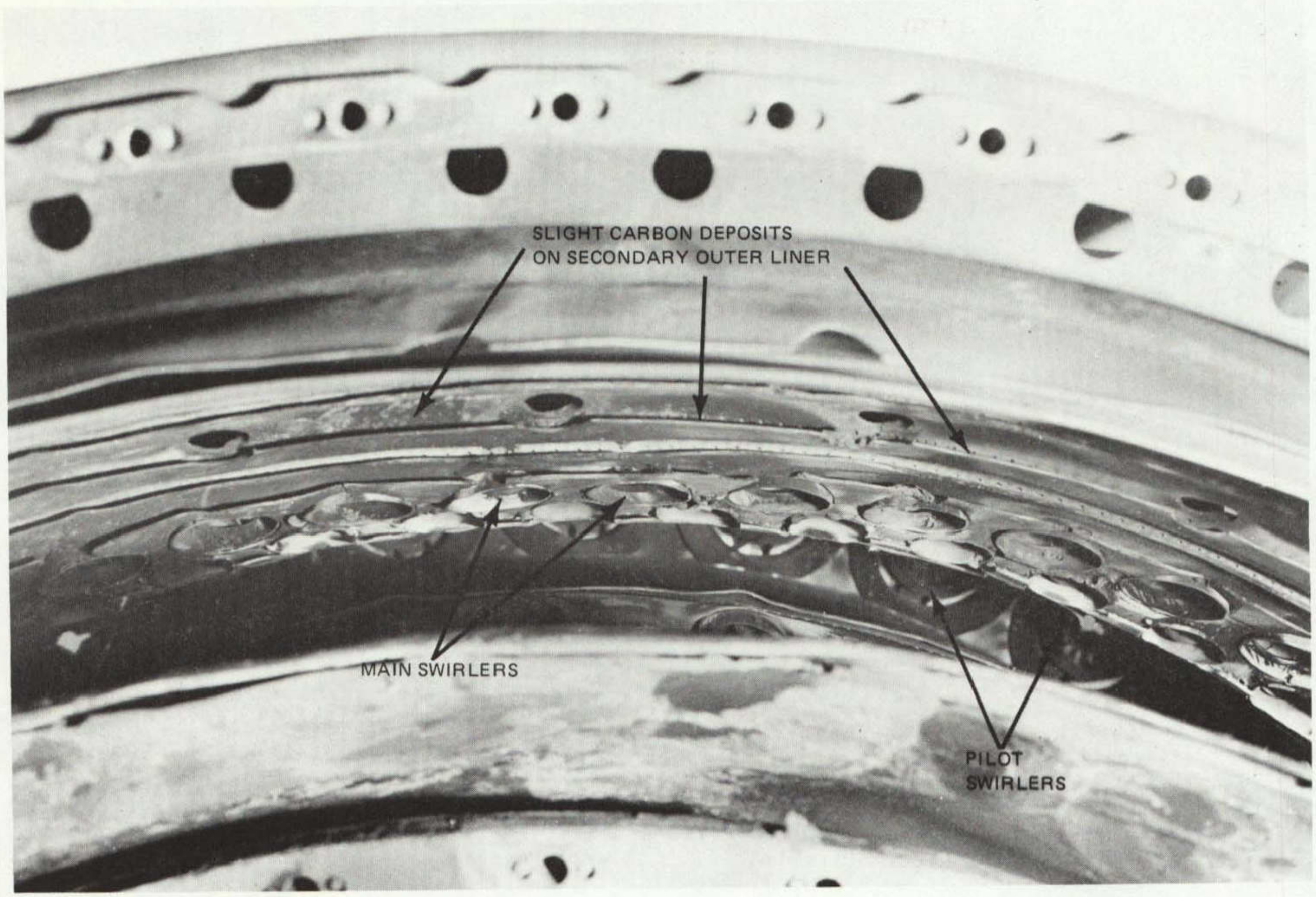


Figure 30 View Looking Upstream, Vorbix Combustor Configuration S-22, Following the Endurance Test on No. 2 Home Heat Fuel

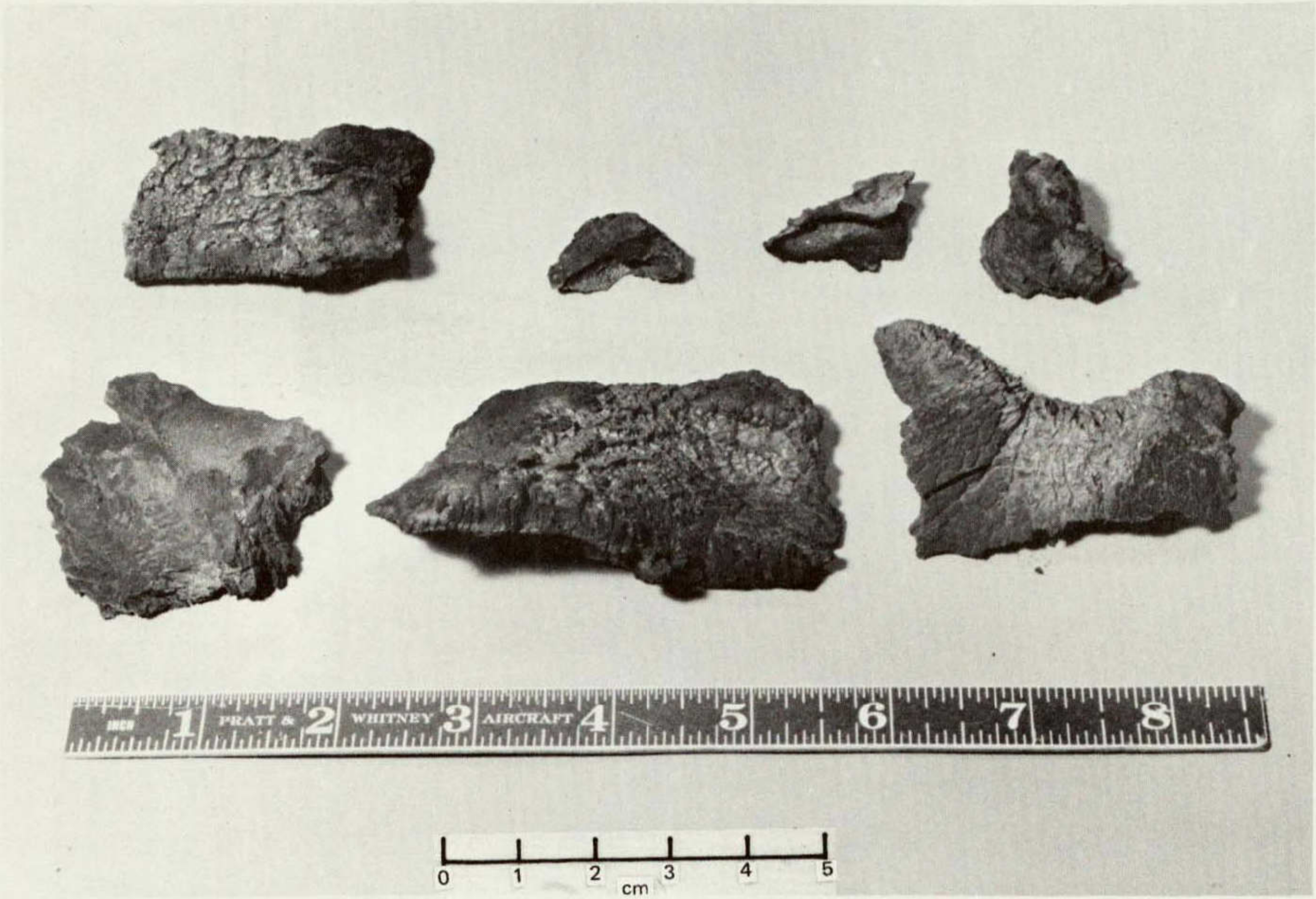


Figure 31 Carbon Deposits Removed from the Vorbix Combustor Pilot Zone Following the Four-Hour Idle Endurance Test on No. 2 Home Heat Fuel

CHAPTER IV SUMMARY OF RESULTS

The Alternate Fuels Addendum test program was conducted to provide an assessment of the effects of increased hydrocarbon fuel aromatic content and increased boiling point for two advanced-technology, low emission combustor concepts. The Hybrid and Vorbix combustors developed in the Experimental Clean Combustor Program represent fundamentally different emission control strategies. The Hybrid is a premix-type concept, where fuel injection and partial premixing occurs prior to fuel entry into the pilot and main burning zones. The Vorbix combustor employs a conventional, direct fuel injection pilot design with main fuel injected directly into the pilot zone exhaust stream. Not unexpectedly, the two combustors responded differently to the four special test fuels in certain performance categories.

At Idle, NO_x and CO emission levels for both the Hybrid and Vorbix combustors were generally higher for the test fuels when compared to Jet A. Hybrid CO emissions exhibited an increasing trend with both aromatic complexity and increased boiling point; however, the trend versus hydrogen content was not maintained with the No. 2 oils. Unburned hydrocarbons exhibited a similar trend in the Vorbix combustor with three of the four test fuels showing higher THC emissions when compared to the baseline fuel. The Hybrid combustor did not exhibit a systematic trend with respect to hydrocarbon emissions.

The only significant emission changes observed at simulated SLTO operation were a modest increase in NO_x level for the Hybrid combustor and a substantial increase in smoke for the Vorbix combustor. In each instance, the increase appeared to correlate with reduction in fuel hydrogen content. The absence of an increasing smoke trend for the Hybrid combustor suggests that intrinsically low smoke concepts, such as the premix-type Hybrid pilot and main zones, will be more tolerant of fuel composition changes which would tend to increase smoke level in a conventional, direct injection combustor.

At simulated altitude conditions, the Hybrid combustor demonstrated a significant deterioration in minimum pressure blow out (MPBO) capability while the Vorbix combustor showed no change in altitude stability between the Jet A baseline and No. 2 Home Heat fuel. In contrast to the deteriorated altitude stability of the Hybrid concept, neither combustor exhibited a penalty in Idle stability (lean blow out) with No. 2 Home Heat fuel. No consistent trend to increased liner temperature was observed at simulated SLTO operation for the range of fuels investigated. However, excessive carbon deposition was observed on the Hybrid pilot flameholder and on localized regions of the Vorbix liner at Idle following endurance testing with No. 2 Home Heat fuel.

CHAPTER V CONCLUDING REMARKS

Selection of the four test fuels was based on anticipated future trends in the composition of jet fuels, both due to broadened specifications for petroleum-derived fuels and consideration of alternate raw material sources. Since synthetic fuels could be produced from a number of raw material sources, such as shale oil or coal, the composition of these fuels is expected to vary widely. The four fuels investigated in this program were chosen to simulate fuels with a higher boiling range and/or varying fractions of aromatics when compared to current Jet A fuel.

As shown in Table I, the Jet A + Xylene and the Jet A + Naphthalene blends meet the boiling range specification for Jet A and are very similar with respect to other Jet A properties, such as viscosity and freezing point. The fuels were custom blended to simulate high aromatic synthetic fuels. The xylene blend represents a simple benzene derivative aromatic and the naphthalene is a more complex aromatic. The No. 2 Diesel and No. 2 Home Heat fuels were chosen to simulate higher boiling fuels with varying fractions of both simple and complex aromatics. Since it was not possible to hold all other fuel properties constant, the impact of certain of these changes may mask the trends associated with the properties under investigation. However, since both No. 2 oils were commercial grade fuels, the changes in viscosity and freezing point are those which would naturally accompany an increase in final boiling point. It probably is not appropriate to consider an increase in final boiling point without these other property changes.

At the outset of the Alternate Fuels program, it was anticipated that the following could result from increasing the aromatic content of the fuel:

- increase in flame radiation and higher combustor metal temperatures
- increase in smoke emission levels
- increase in NO_x emission levels
- increase in carbon deposition tendencies

It was also anticipated that increasing the final boiling point would lower the volatility making such fuels more difficult to vaporize and burn. This could be reflected by a reduction in Idle efficiency and stability (blow out).

With the exception of an increase in exhaust smoke for the Vorbix combustor (conventional pilot), carbon deposition problems relatable to the No. 2 Home Heat fuel, and a deterioration in altitude stability for the Hybrid combustor (premix-type pilot), these expectations have not been realized. The lack of a strong negative impact in advanced technology hardware suggests that broadening of aviation turbine fuel specifications in the directions investigated may be one approach to possibly increasing the available fuel supply for future aircraft operations. In particular, the differing responses of the two combustor types to changes

in fuel composition and physical properties suggest the possibility that selection of a low-emission combustor concept might be influenced by the need to accommodate specific fuel characteristics.

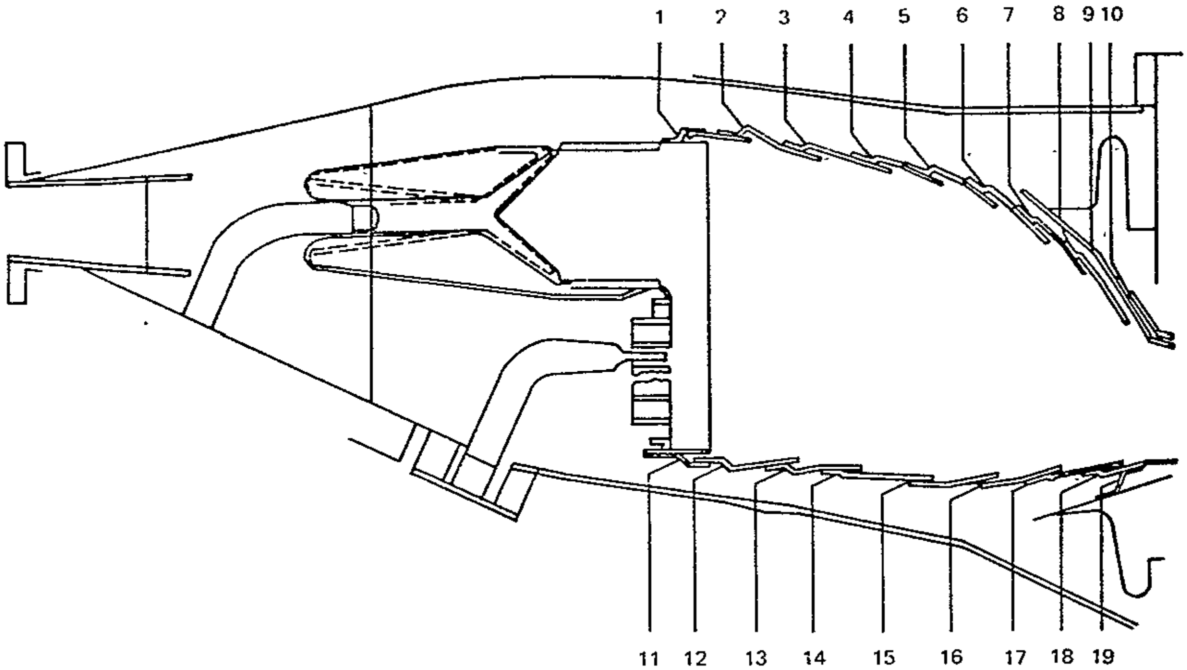
In interpreting the results of this program, it should be realized that the scope of the program was limited and only general trends could be observed for each of the fuels tested. In particular, the limited endurance testing may have prevented identification of trends which, although small, would have a detrimental impact in long-term operation. The following additional research is suggested to better define the suitability of alternate fuels for aircraft gas turbine applications:

- better definition of all fuel property changes which will accompany composition changes for fuels refined from identifiable feedstocks;
- definition of whether such property changes are or can be made acceptable for aircraft flight operations;
- actual engine testing as proposed alternate fuels and production-candidate advanced technology combustors became better defined.

APPENDIX A

APPENDIX A

CONFIGURATION H 6



COOLING HOLE PATTERN

INNER LINER					OUTER LINER			
LOUVER	DIA. m X 10^{-3}	# HOLES	AREA m^2 X 10^{-4}		LOUVER	DIA m X 10^{-3}	# HOLES	AREA m^2 X 10^{-4}
1	1.32	85	1.17		11	1.32	110	1.51
2	1.32	85	1.17		12	1.32	110	1.51
3	1.32	85	1.17		13	1.32	110	1.51
4	1.32	85	1.17		14	1 32	110	1.51
5	1.32	92	1.26		15	1.93	60	1.75
6	1.32	81	1.11		16	2 16	60	2.19
7	1 32	92	1.26		17	2 31	60	2.52
8	1.32	122	1 67		18	2.36	60.	2.63
9	1 59	85	1 68		19	1.59	110	2.17
10	1 59	85	1 68					

		AREA $m^2 \times 10^{-4}$
PILOT BURNER FLAMEHOLDER	94 @ 0 80 x 10^{-2} DIAMETER	47.26 A_{CD} (EFFECTIVE AREA)
PILOT BURNER FLAMEHOLDER WEEP		7.43 A_{CD} (EFFECTIVE AREA)
MAIN BURNER OUTER SWIRLER	11 LEFT HAND SWIRLERS	62.31 A_{CD} (EFFECTIVE AREA)
MAIN BURNER INNER SWIRLER	11 RIGHT HAND SWIRLERS	34.42 A_{CD} (EFFECTIVE AREA)
BULKHEAD COOLING	172 @ 0 411 X 10^{-2}m DIAMETER	22.87
FLAMEHOLDER COOLING (ON OUTER WALL)	39 @ 0.254 X 10^{-2}m DIAMETER	1.97
FLAMEHOLDER COOLING (ON INNER WALL)	38 @ 0.254 X 10^{-2} m DIAMETER	1.92
FINWALL® (INNER WALL)	1.01% W_{AB} (BURNER AIRFLOW)	
FINWALL® (OUTER WALL)	1.23% W_{AB} (BURNER AIRFLOW)	
SIDEWALL COOLING	5 00% W_{A4} (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (INNER WALL)	7.5% W_{A4} (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (OUTER WALL)	8.4% W_{A4} (TOTAL AIRFLOW – STATION 4)	
PILOT BURNER NOZZLE – P/N	DLN 27700-11 10 LOCATIONS	
MAIN BURNER NOZZLE – P/N	LOW ΔP 11 LOCATIONS	

MODIFICATIONS REFERENCE H5

ELIMINATE INNER LINER DILUTION COOLING

ADD 35% OF DILUTION AIR TO BULKHEAD COOLING

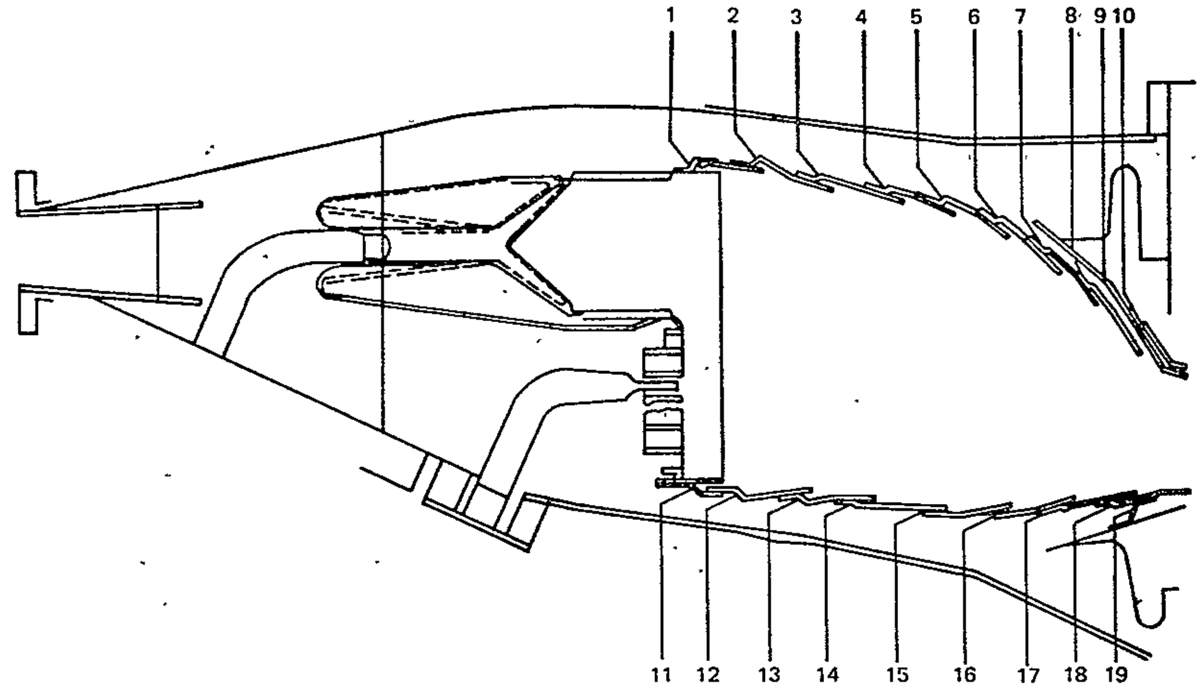
ADD 65% OF DILUTION AIR TO OUTER LINER FLAMEHOLDER COOLING

PRIMARY FUEL INJECTORS EXTENDED ONE INCH DOWNSTREAM

INCREASE PILOT BURNER PREMIX PASSAGE AIRFLOW

APPENDIX A (Cont'd)

CONFIGURATION H7



COOLING HOLE PATTERN

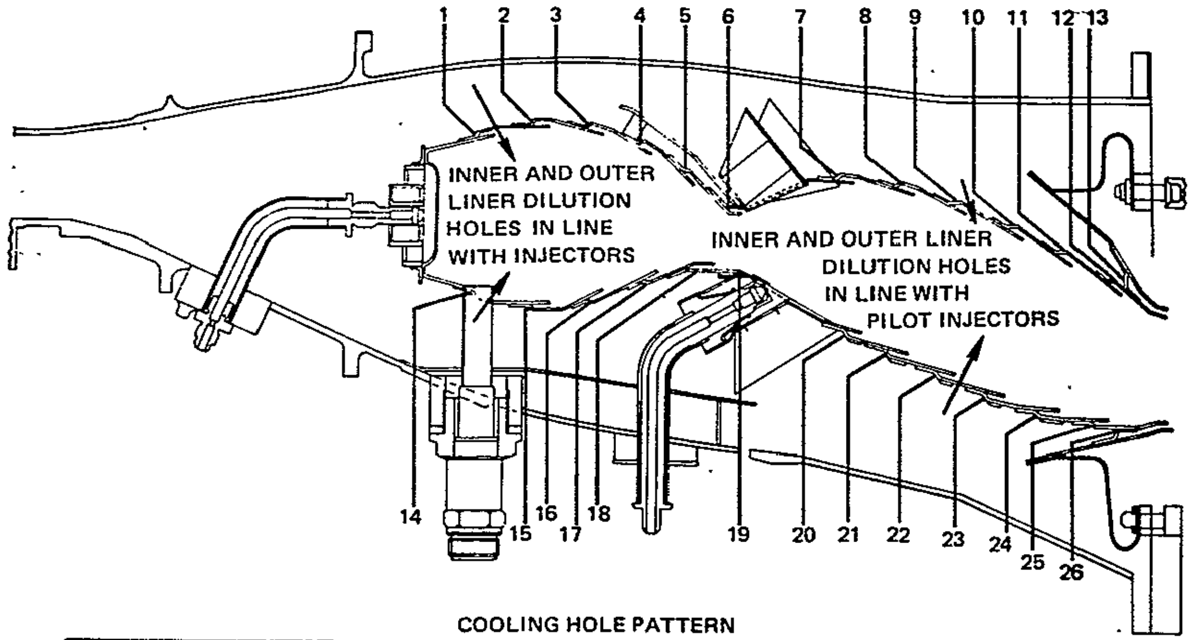
INNER LINER				OUTER LINER			
LOUVER	DIA. m X 10^{-3}	= HOLES	AREA m^2 X 10^{-4}	LOUVER	DIA. m X 10^{-3}	= HOLES	AREA m^2 X 10^{-4}
1	1.32	85	1.17	11	1.32	110	1.51
2	1.32	85	1.17	12	1.32	110	1.51
3	1.32	85	1.17	13	1.32	110	1.51
4	1.32	85	1 17	14	1.32	110	1.51
5	1.32	92	1.26	15	1.93	60	1.75
6	1.32	81	1.11	16	2.16	60	2.19
7	1.32	92	1.26	17	2.31	60	2.52
8	1.32	122	1.67	18	2 36	60	2.63
9	1 59	85	1.68	19	1.59	110	2.17
10	1.59	85	1.68				

		AREA m^2 X 10^{-4}
PILOT BURNER FLAMEHOLDER	94 @ 0.80 X 10^{-2}m DIAMETER	47.26
PILOT BURNER FLAMEHOLDER WEEP		7.43 A_{CD} (EFFECTIVE AREA)
MAIN BURNER OUTER SWIRLER	11 LEFT HAND SWIRLERS	62.31 A_{CD} (EFFECTIVE AREA)
MAIN BURNER INNER SWIRLER	11 RIGHT HAND SWIRLERS	34.42 A_{CD} (EFFECTIVE AREA)
BULKHEAD COOLING	172 @ 0.411 X 10^{-2}m DIAMETER	22.87
FLAMEHOLDER COOLING (ON OUTER WALL)	39 @ 0.254 X 10^{-2}m DIAMETER	1.97
FLAMEHOLDER COOLING (ON INNER WALL)	38 @ 0.254 X 10^{-2}m DIAMETER	1.92
FINWALL® (INNER WALL)	1.01% W_{AB} (BURNER AIRFLOW)	
FINWALL ® (OUTER WALL)	1.23% W_{AB} (BURNER AIRFLOW)	
SIDEWALL COOLING	5.00% W_{A4} (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (INNER WALL)	7.5% W_{A4} (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (OUTER WALL)	8.4% W_{A4} (TOTAL AIRFLOW – STATION 4)	
PILOT BURNER NOZZLE – P/N	DLN 34800 10 LOCATIONS	
MAIN BURNER NOZZLE – P/N	LOW ΔP 11 LOCATIONS	

MODIFICATIONS REFERENCE H6

INSTALL SOLID CONE PILOT BURNER FUEL NOZZLES

CONFIGURATION S 20



COOLING HOLE PATTERN

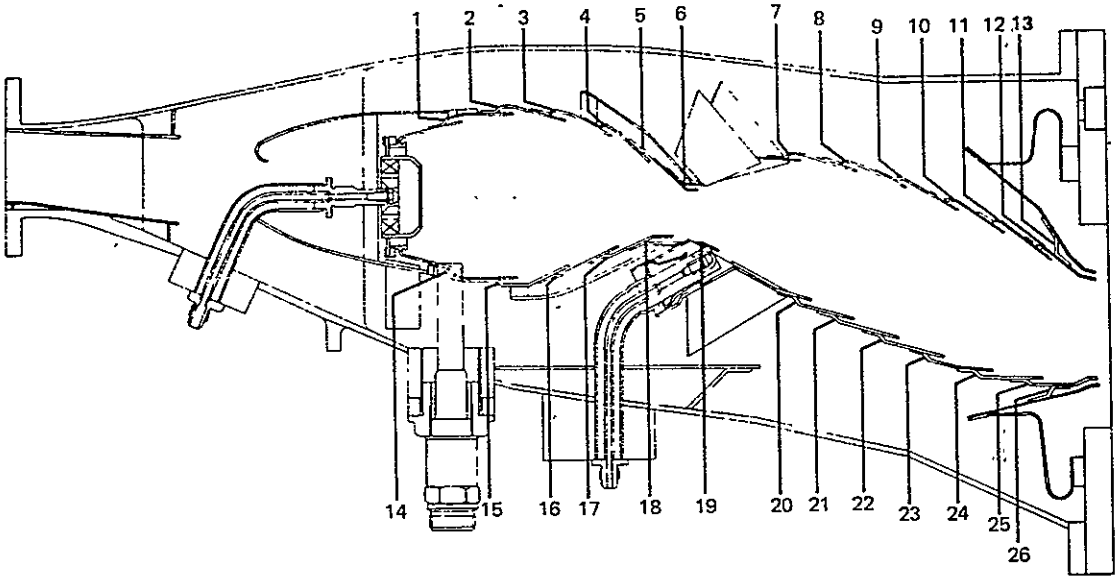
INNER LINER				OUTER LINER			
LOUVER	DIA. $m \times 10^{-3}$	#HOLES	AREA $m^2 \times 10^{-4}$	LOUVER	DIA. $m \times 10^{-3}$	#HOLES	AREA $m^2 \times 10^{-4}$
1	1.63	84	1.74	14	2.34	84	3.61
2	1.63	84	1.74	15	1.63	84	1.74
3	1.63	84	1.74	16	1.63	84	1.74
4	1.63	84	1.74	17	1.63	84	1.74
5	1.96	84	2.52	18	1.80	84	2.15
6	2.27	84	3.45	19	2.08	130	4.43
7	1.93	85	2.49	20	1.63	99	2.05
8	1.32	85	1.17	21	1.63	99	2.05
9	1.32	85	1.17	22	1.32	118	1.62
10	1.32	85	1.17	23	1.32	95	1.30
11	1.32	85	1.17	24	1.32	106	1.45
12	1.32	85	1.17	25	1.79	85	2.11
13	1.32	85	1.17	26	1.32	110	1.51

		AREA $m^2 \times 10^{-4}$
PILOT BURNER SWIRLER	7 LEFT HAND SWIRLERS	24.39 A_{CD} (EFFECTIVE AREA)
BULKHEAD COOLING	147 @ 0.226×10^{-2}m DIAMETER	5.90
MAIN BURNER NOZZLE COOLING	52 @ 0.254×10^{-2}m DIAMETER	2.63
PILOT BURNER DILUTION (INNER WALL)	7 @ 1.631×10^{-2}m DIAMETER	14.62
PILOT BURNER DILUTION (OUTER WALL)	7 @ 1.631×10^{-2}m DIAMETER	14.62
MAIN BURNER SWIRLERS	28 RIGHT HAND SWIRLERS	101.16 A_{CD} (EFFECTIVE AREA)
SIDEWALL COOLING	5% WA_4 (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (INNER WALL)	7.5% W_{A4} (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (OUTER WALL)	8.4% W_{A4} (TOTAL AIRFLOW – STATION 4)	
PILOT BURNER NOZZLE	DLN 27700-11, 7 LOCATIONS	
MAIN BURNER NOZZLE	DLN 27700-11, 13 LOCATIONS	
MAIN BURNER DILUTION (INNER WALL)	7 @ 1.664×10^{-2}m DIAMETER	15.22
MAIN BURNER DILUTION (OUTER WALL)	7 @ 1.664×10^{-2}m DIAMETER	15.22

MODIFICATIONS REFERENCE S 19

INCREASE PILOT BURNER SWIRLER AIR FLOW
DECREASE MAIN BURNER SWIRLER AIR FLOW

CONFIGURATION S22



COOLING HOLE PATTERN

INNER LINER				OUTER LINER			
LOUVER	DIA. $m \times 10^{-3}$	#HOLES	AREA $m^2 \times 10^{-4}$	LOUVER	DIA. $m \times 10^{-3}$	#HOLES	AREA $m^2 \times 10^{-4}$
1	1 63	84	1.74	14	2 34	84	3.61
2	1.63	84	1.74	15	1.63	84	1.74
3	1 63	84	1.74	16	1.63	84	1.74
4	1.63	84	1.74	17	1.63	84	1.74
5	1.96	84	2 52	18	1.80	84	2 15
6	2 27	84	3.45	19	2 08	130	4.43
7	1.93	85	2.49	20	1.63	99	2.05
8	1.32	85	1.17	21	1.63	99	2.05
9	1.32	85	1.17	22	1.32	118	1.62
10	1.32	85	1.17	23	1 32	95	1.30
11	1.32	85	1 17	24	1 32	106	1.45
12	1.32	85	1 17	25	1.79	85	2.11
13	1 32	85	1.17	26	1.32	110	1.51

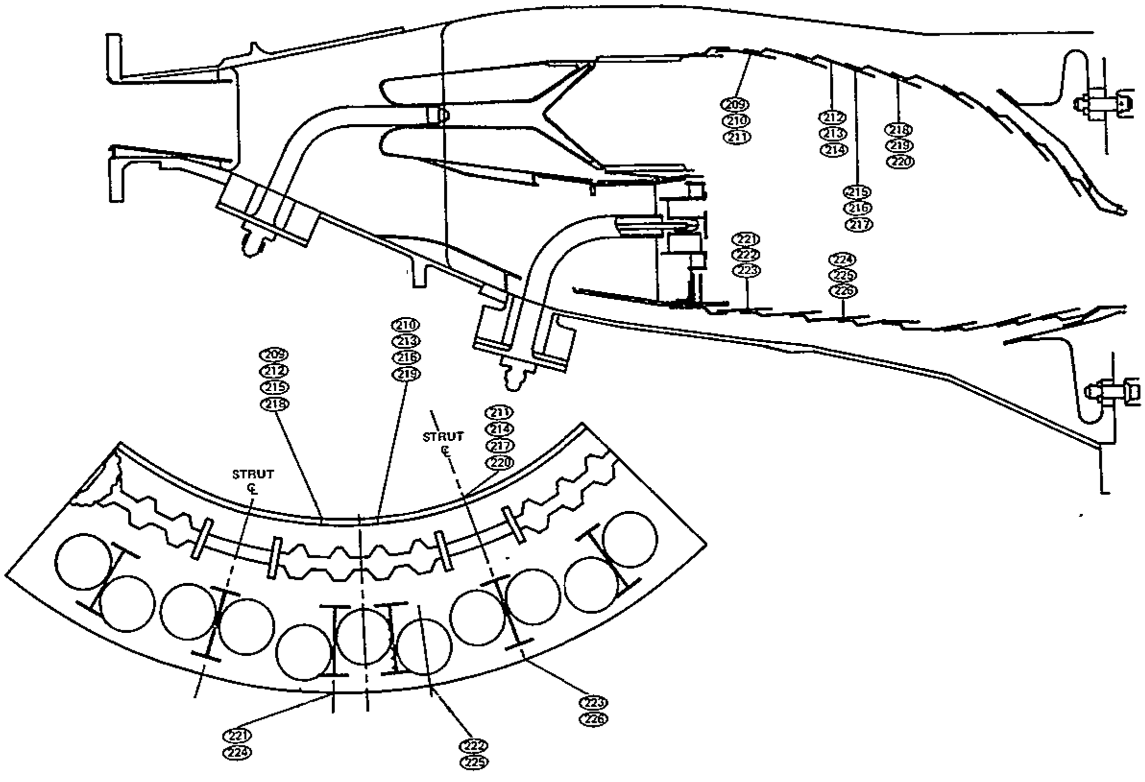
		AREA $m^2 \times 10^{-4}$
PILOT BURNER SWIRLER (INCLUDING SLOTS IN CENTER TUBE OF SWIRLER)	7 LEFTHAND SWIRLERS	27.46 A_{CD} (EFFECTIVE AREA)
BULKHEAD COOLING	140 @ 0.234 X 10^{-2}m DIAMETER	6.09
MAIN BURNER NOZZLE COOLING	52 @ 0.254 X 10^{-2}m DIAMETER	2.63
PILOT BURNER DILUTION (INNER WALL ROW 1)	7 @ 1.63 X 10^{-2}m DIAMETER	14.62
PILOT BURNER DILUTION (OUTER WALL ROW 14)	7 @ 1.63 X 10^{-2}m DIAMETER	14.62
MAIN BURNER SWIRLERS	28 RIGHT HAND SWIRLERS	
SIDEWALL COOLING	5% W_{A4} (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (INNER WALL)	7.5% W_{A4} (TOTAL AIRFLOW – STATION 4)	
TURBINE COOLING (OUTER WALL)	8.4% W_{A4} (TOTAL AIRFLOW – STATION 4)	
PILOT BURNER NOZZLE	DLN 27700-13, 7 LOCATIONS	
MAIN BURNER NOZZLE	DLN 27700-11, 13 LOCATIONS	
MAIN BURNER DILUTION OUTER WALL		15.22
MAIN BURNER DILUTION INNER WALL		15.22

MODIFICATIONS REFERENCE S21

INSTALL HOOD
INSTALL NEW SWIRLER – TORROIDAL DEFLECTOR WITH 3.3 X 10^{-2}m DIAMETER HOLE.
ADD OUTER LINER SCOOP
REVISE BULKHEAD WITH COOLING AIR ENTERING THROUGH RING CONCENTRIC WITH SWIRLER.
ADD TEMPERATURE-SENSITIVE PAINT ON LINER (INSIDE AND OUT)
REMOVE PREMIXING TUBE FROM MAIN BURNER.

APPENDIX B

APPENDIX B



HYBRID LINER TEMPERATURE DATA (K)

FUEL = JET A

	IDLE				SLTO		
POINT	8	1	6	7	19	23	24
F/A PILOT	0.0102	0.0123	0.0157	0.0077	0.0076	0.0075	0.0076
F/A TOTAL	0.0102	0.0123	0.0157	0.0077	0.0223	0.0199	0.0160
T_{T4} ~ K	430	429	426	427	767	767	773
T/C 209	661	682	696	537	941	935	932
T/C 210	528	539	559	445	869	866	867
T/C 211	587	593	614	482	903	897	892
T/C 212	545	570	580	456	878	873	829
T/C 213	490	498	508	438	856	852	852
T/C 215	677	722	742	509	1045	1036	1029
T/C 216	561	567	595	454	1004	998	994
T/C 217	521	536	554	464	956	964	956
T/C 219	567	583	598	457	981	973	968
T/C 220	518	528	549	464	970	973	963
T/C 223	442	446	448	428	807	808	793
T/C 224	452	459	464	433	850	836	822
T/C 225	460	470	478	433	914	891	856
T/C 226	461	471	479	433	870	875	829

APPENDIX B (Cont'd)

HYBRID LINER TEMPERATURE DATA (Cont'd)

FUEL = NO. 2 DIESEL

	IDLE				SLTO			
POINT	305	306	307	308	318	319	320	321
F/A PILOT	0 0099	0.0125	0.0139	0.0161	0.0077	0.0077	0.0077	0 0077
F/A TOTAL	0.0099	0.0125	0.0139	0.0161	0 0226	0.0200	0.0181	0.0160
T_{T4} ~ K	432	430	430	429	767	767	771	766
T/C 209	656	694	706	717	938	935	922	914
T/C 210	551	572	579	588	880	877	865	855
T/C 211	609	645	658	679	886	883	873	867
T/C 212	542	572	582	595	842	841	829	822
T/C 213	519	529	534	542	871	868	854	844
T/C 215	660	707	724	744	1016	1017	1003	996
T/C 216	640	652	657	667	1035	1030	1008	995
T/C 217	563	599	617	656	998	998	981	966
T/C 219	647	666	674	684	998	994	976	963
T/C 220	548	575	592	631	991	988	971	959
T/C 223	444	453	457	465	812	809	797	785
T/C 224	429	436	439	489	893	868	844	819
T/C 225	456	469	476	489	897	879	861	838
T/C 226	465	483	493	412	858	849	834	813

FUEL = NO. 2 HOME HEAT

	IDLE				SLTO			
POINT	205	206	207	208	218	219	220	221
F/A PILOT	0.0102	0.0125	0.0142	0.0160	0.0076	0.0077	0.0072	0.0076
F/A TOTAL	0 0102	0.0125	0 0142	0.0160	0 0223	0.0199	0.0169	0.0159
T_{T4} ~ K	431	428	428	431	772	759	767	772
T/C 209	666	686	688	720	927	912	938	923
T/C 210	546	573	587	612	879	859	864	860
T/C 211	631	672	712	736	896	876	878	874
T/C 212	539	567	587	608	843	824	840	832
T/C 213	509	527	542	566	867	846	858	849
T/C 215	657	706	742	776	1026	994	1012	998
T/C 216	616	646	665	714	1024	1001	1011	997
T/C 217	573	631	704	774	991	948	962	967
T/C 219	606	647	671	717	998	972	983	968
T/C 220	556	594	653	731	994	956	961	959
T/C 223	447	462	473	489	828	804	807	803
T/C 224	457	473	443	456	871	839	855	836
T/C 225	454	474	490	512	898	848	849	832
T/C 226	467	495	519	552	889	919	862	853

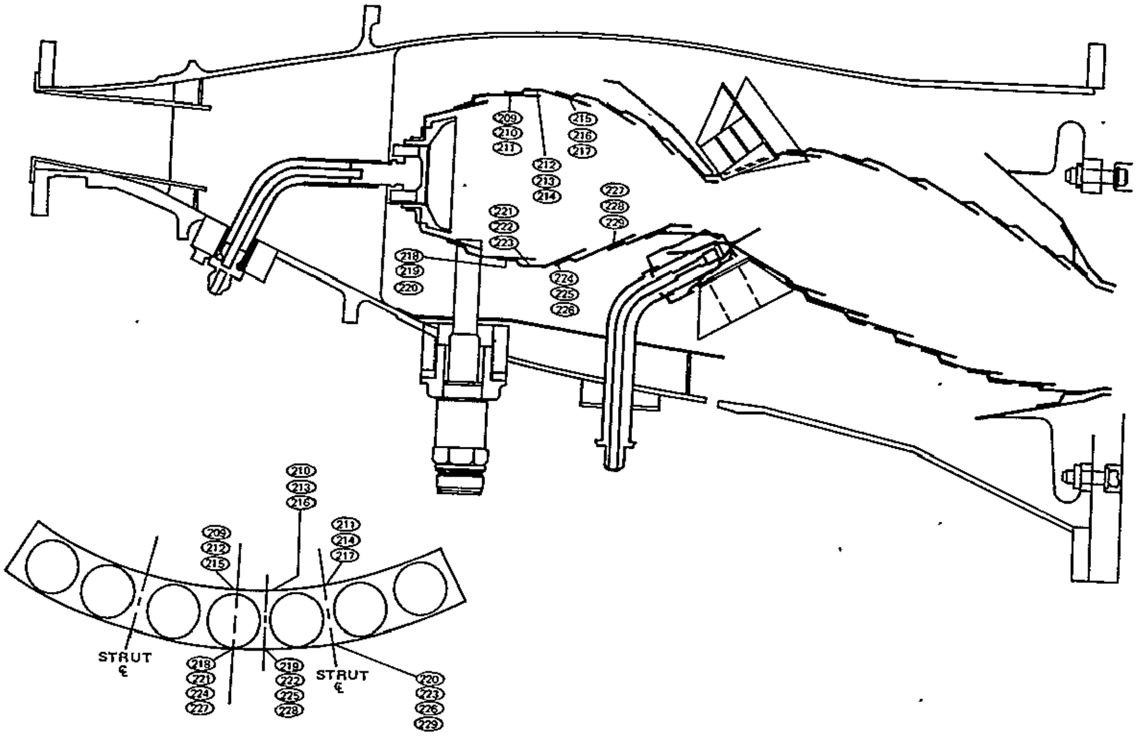
HYBRID LINER TEMPERATURE DATA (Cont'd)

FUEL = JET A + XYLENE

	IDLE					SLTO			
POINT	405	406	406	407	409	418	419	420	421
F/A PILOT	0.0101	0.0130	0.0132	0.0141	0.0164	0.0076	0.0077	0.0076	0.0077
F/A TOTAL	0.0101	0.0130	0.0132	0.0141	0.0164	0.0224	0.0199	0.0180	0.0161
$T_{T4} \sim K$	426	424	429	426	431	759	772	772	774
T/C 209	660	696	699	698	692	927	931	924	921
T/C 210	556	569	576	572	590	876	881	873	871
T/C 211	637	695	692	691	697	891	897	889	888
T/C 212	554	578	589	594	615	831	837	832	836
T/C 213	507	526	533	535	552	855	862	854	854
T/C 215	659	726	740	748	772	1032	1038	1030	1029
T/C 216	618	654	663	666	688	1013	1016	1000	997
T/C 217	591	667	674	691	721	979	979	968	971
T/C 219	446	656	666	668	695	987	991	975	974
T/C 220	563	625	632	654	693	985	984	971	1025
T/C 223	440	454	461	462	473	809	813	840	801
T/C 224	433	442	446	479	495	859	854	861	832
T/C 225	449	469	475	479	496	894	883	861	844
T/C 226	459	488	495	504	524	882	866	869	838

FUEL = JET A + NAPHTHALENE

	IDLE				SLTO			
POINT	505	506	507	508	518	519	520	521
F/A PILOT	0.0103	0.0126	0.0140	0.0160	0.0076	0.0076	0.0076	0.0076
F/A TOTAL	0.0103	0.0126	0.0140	0.0160	0.0223	0.0199	0.0179	0.0162
$T_{T4} \sim K$	427	428	426	427	766	771	771	768
T/C 209	645	681	679	689	928	926	926	921
T/C 210	545	567	566	584	877	873	871	863
T/C 211	611	640	652	667	882	881	882	876
T/C 212	521	557	571	592	840	837	832	826
T/C 213	507	527	531	551	863	860	855	847
T/C 215	624	698	723	744	1017	1012	1004	999
T/C 216	611	648	651	690	1027	1017	1007	994
T/C 217	575	632	682	718	1006	994	976	962
T/C 219	611	651	657	701	994	984	975	964
T/C 220	564	600	649	699	1004	991	974	961
T/C 223	445	458	464	472	817	814	808	794
T/C 224	453	469	479	491	868	853	832	823
T/C 225	453	471	483	498	892	873	858	839
T/C 226	464	491	508	527	866	859	852	826



VORBIX LINER TEMPERATURE DATA (K)

FUEL = JET A

	IDLE					SLTO		
POINT	2	3	4	5	POINT	16	19	20
F/A PILOT	0.0125	0.0158	0.0080	0.0059		0.0045	0.0045	0.0045
F/A TOTAL	0.0125	0.0158	0.0080	0.0059		0.0226	0.0199	0.0159
$T_{T4} \sim K$	427	427	426	428		769	768	768
T/C 213	599	635	541	498		842	843	845
T/C 215	1002	1040	819	652		977	964	963
T/C 224	836	925	638	566		953	954	932
T/C 225	689	708	1025	698		1022	1043	1017
T/C 226	1112	1022	724	641		999	998	965
T/C 229	1161	1064	767	668		1026	1020	993

VORBIX LINER TEMPERATURE DATA (Cont'd)

FUEL = NO. 2 DIESEL

	IDLE						SLTO			
POINT	302	302	303	304	305	POINT	318	319	320	321
F/A PILOT	0.0126	0.0124	0.0160	0.0078	0.0058		0.0045	0.0040	0.0044	0.0044
F/A TOTAL	0.0126	0.0124	0.0160	0.0078	0.0058		0.0225	0.0200	0.0161	0.0139
T_{T4} ~ K	426	429	429	427	427		771	765	768	770
T/C 213	639	744	653	565	491		828	816	819	828
T/C 216	989	983	966	665	559		971	932	918	921
T/C 224	893	860	901	684	548		911	889	962	958
T/C 225	757	780	772	991	648		1072	994	989	988
T/C 226	986	981	777	752	655		1036	992	1015	1011
T/C 229	1225	1189	1152	953	780		1054	1008	966	972

FUEL = NO. 2 HOME HEAT

	IDLE						SLTO			
POINT	202	202	203	204	205	POINT	218	219	220	221
F/A PILOT	0.0124	0.0125	0.0159	0.0079	0.0060		0.0045	0.0044	0.0044	0.0045
F/A TOTAL	0.0124	0.0125	0.0159	0.0079	0.0060		0.0225	0.0196	0.0158	0.0141
T_{T4} ~ K	426	427	426	427	426		768	767	967	768
T/C 213	578	622	662	549	468		822	823	819	751
T/C 215	968	973	1063	697	581		949	945	947	826
T/C 224	897	892	771	803	638		1018	1002	1022	893
T/C 225	867	813	893	564	503		840	854	864	907
T/C 226	972	951	957	647	555		934	929	945	955
T/C 229	1037	1068	883	671	566		925	916	926	1005

VORBIX LINER TEMPERATURE DATA (Cont'd)

FUEL = JET A + XYLENE

	IDLE						SLTO				
POINT	402	402	403	404	405	POINT	418	419	420	420	421
F/A PILOT	0.0124	0.0122	0.0156	0.0077	0.0060	0.0059	0.0044	0.0045	0.0045	0.0044	0.0044
F/A TOTAL	0.0124	0.0122	0.0156	0.0077	0.0060	0.0059	0.0221	0.0200	0.0159	0.0161	0.0142
$T_{T4} \sim K$	434	429	429	429	424	428	768	768	771	772	771
T/C 213	713	706	781	501	469	472	822	824	822	828	826
T/C 215	1099	1082	1066	732	630	629	942	942	940	958	979
T/C 224	1073	1043	805	747	675	680	1013	1016	1015	1004	1026
T/C 225	790	749	867	577	512	512	938	847	852	861	869
T/C 226	1012	994	1049	739	608	602	930	920	924	939	947
T/C 229	1084	1044	1076	745	624	624	868	913	922	916	926

FUEL = JET A + NAPHTHALENE

	IDLE						SLTO				
POINT	502	502	503	504	505	POINT	518	519	520	521	521
F/A PILOT	0.0126	0.0126	0.0160	0.0080	0.0061		0.0044	0.0043	0.0045	0.0045	0.0045
F/A TOTAL	0.0126	0.0126	0.0160	0.0080	0.0061		0.0220	0.0198	0.0158	0.0135	0.0137
$T_{T4} \sim K$	424	425	426	427	424		766	767	770	767	768
T/C 213	680	694	871	556	481		846	841	854	851	847
T/C 215	961	973	1232	633	570		940	978	964	962	961
T/C 224	884	887	824	572	536		903	901	912	907	915
T/C 225	856	819	937	954	676		1027	1035	1024	1019	1051
T/C 226	868	826	719	712	584		1008	1009	1020	1020	1045
T/C 229	988	1094	1317	862	667		1020	1024	1037	1036	1063

APPENDIX C

APPENDIX C

Configuration H-6

Point Number	Airflow - Total kg/s	Airflow-Combustor kg/s	Fuel Flow - Pilot kg/s	Fuel Flow - Main kg/s	Fuel Flow - Total kg/s	Fuel Temperature K	Inlet Total Temperature K	Inlet Total Pressure — atm	Fuel-Air Ratio Metered (M)	Fuel-Air Ratio Carbon Balance (CB)	Fuel-Air (CB) / Fuel-Air (M)	Ideal Combustor Exit Temperature K	Maximum Combustor Exit Temperature K	Pattern Factor	Reference Velocity - m/s	CO_2 - % Volume	O_2 - % Volume	CO (EI)	THC (EI)	NO_X (EI)	Gas Sample Combustion Efficiency	Humidity (g H_2O/kg air)	SAE Smoke Number	Comments
1	4.84	3.85	0.0472	0.0	0.0472	302.	429.	2.93	0.0122	0.0	0.0	902.	1821.	1.94	17.9	0.0	0.0	0.0	0.0	0.0	0.0	1.0		JETA
5	4.97	3.95	0.0485	0.0	0.0485	301.	427.	2.93	0.0123	0.0090	0.73	901.	0.	0.0	18.3	1.84	18.0	7.9	4.4	4.1	99.3	1.0		JETA
6	4.94	3.93	0.0612	0.0	0.0612	301.	425.	2.90	0.0156	0.0117	0.75	1015.	0.	0.0	18.3	2.31	17.1	56.6	4.4	4.9	98.2	1.0		JETA
7	5.04	4.02	0.0307	0.0	0.0307	301.	427.	2.91	0.0076	0.0029	0.38	732.	0.	0.0	18.8	0.54	20.2	198.5	0.0	1.0	95.4	1.0		JETA
8	4.81	3.82	0.0390	0.0	0.0390	300.	430.	2.94	0.0102	0.0074	0.73	829.	0.	0.0	17.7	1.50	18.7	11.3	11.7	2.7	98.4	0.9		JETA
19	8.71	6.93	0.0526	0.1019	0.1545	300.	767.	6.92	0.0223	0.0215	0.96	1516.	0.	0.0	24.4	4.32	13.8	17.3	2.1	11.2	99.4	1.3		JETA
23	8.63	6.87	0.0517	0.0852	0.1369	300.	767.	6.91	0.0199	0.0189	0.95	1445.	0.	0.0	24.2	3.77	14.6	26.9	5.7	10.4	98.7	1.1		JETA
24	8.60	6.84	0.0524	0.0565	0.1089	301.	770.	6.79	0.0159	0.0150	0.94	1323.	0.	0.0	24.7	2.92	16.0	73.8	9.6	7.5	97.2	1.5	SN=5	JETA
24	8.63	6.86	0.0522	0.0572	0.1094	301.	775.	6.80	0.0159	0.0	0.0	1327.	1547.	0.40	24.8	0.0	0.0	0.0	0.0	0.0	0.0	1.3		JETA

Configuration H-6 (Cont'd)

Point Number	Airflow - Total kg/s	Airflow-Combustor kg/s	Fuel Flow - Pilot kg/s	Fuel Flow - Main kg/s	Fuel Flow - Total kg/s	Fuel Temperature K	Inlet Total Temperature K	Inlet Total Pressure – atm	Fuel-Air Ratio Metered (M)	Fuel-Air Ratio Carbon Balance (CB)	Fuel-Air (CB) / Fuel-Air (M)	Ideal Combustor Exit Temperature K	Maximum Combustor Exit Temperature K	Pattern Factor	Reference Velocity - m/s	CO_2 - % Volume	O_2 - % Volume	CO (EI)	THC (EI)	NO_X (EI)	Gas Sample Combustion Efficiency	Humidity (g H_2O/kg air)	SAE Smoke Number	Comments
318	8.60	6.85	0.0524	0.1019	0.1543	300.	767.	6.82	0.0225	0.0212	0.94	1523.	0.	0.0	24.4	4.34	14.1	7.8	0.7	11.6	99.7	1.5	SN=2	DIESEL
319	8.63	6.87	0.0531	0.0841	0.1372	300.	767.	6.85	0.0200	0.0186	0.93	1445.	0.	0.0	24.4	3.82	14.9	14.9	1.2	10.3	99.5	1.7	SN=1	DIESEL
320	8.59	6.83	0.0524	0.0711	0.1235	300.	770.	6.86	0.0181	0.0167	0.92	1391.	0.	0.0	24.4	3.40	15.5	32.3	2.8	9.1	98.9	1.7	SN=1	DIESEL
321	8.68	6.91	0.0529	0.0578	0.1107	300.	765.	6.84	0.0160	0.0142	0.89	1322.	0.	0.0	24.6	2.81	16.5	66.9	10.5	8.3	97.2	1.7	SN=2	DIESEL
321	8.68	6.91	0.0520	0.0566	0.1086	300.	771.	6.82	0.0157	0.0	0.0	1317.	1556.	0.44	24.8	0.0	0.0	0.0	0.0	0.0	0.0	1.7		DIESEL
505	4.78	3.80	0.0390	0.0	0.0390	296.	427.	2.93	0.0103	0.0081	0.79	830.	0.	0.0	17.6	1.73	18.3	7.7	5.1	2.3	99.2	1.3		JETA+NAP
506	4.85	3.85	0.0484	0.0	0.0484	295.	428.	2.93	0.0126	0.0108	0.86	911.	0.	0.0	17.8	2.25	17.5	14.7	4.4	4.3	99.1	1.3		JETA+NAP
507	4.85	3.86	0.0540	0.0	0.0540	296.	426.	2.95	0.0140	0.0127	0.91	960.	0.	0.0	17.7	2.59	17.0	39.6	3.6	5.0	98.7	1.3		JETA+NAP
507	4.89	3.89	0.0541	0.0	0.0541	296.	427.	2.93	0.0139	0.0	0.0	958.	1793.	1.57	18.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4		JETA+NAP
508	4.88	3.88	0.0619	0.0	0.0619	296.	427.	2.95	0.0159	0.0141	0.89	1028.	0.	0.0	17.8	2.82	16.5	87.2	4.2	5.2	97.5	1.3		JETA+NAP
518	8.67	6.91	0.0522	0.1018	0.1540	297.	766.	6.87	0.0223	0.0211	0.95	1515.	0.	0.0	24.5	4.37	14.3	9.1	0.7	13.1	99.7	1.7	SN=4	JETA+NAP
519	8.62	6.85	0.0519	0.0843	0.1362	298.	770.	6.88	0.0199	0.0186	0.93	1446.	0.	0.0	24.4	3.84	15.1	15.0	1.3	11.3	99.5	1.7		JETA+NAP
520	8.72	6.94	0.0526	0.0714	0.1240	298.	770.	6.82	0.0179	0.0162	0.91	1384.	0.	0.0	24.9	3.29	15.8	42.7	7.3	8.8	98.2	1.5	SN=2	JETA+NAP
521	8.70	6.93	0.0529	0.0588	0.1117	298.	768.	6.87	0.0161	0.0143	0.89	1328.	0.	0.0	24.6	2.86	16.6	68.4	14.1	7.8	96.8	1.6	SN=3	JETA+NAP
521	8.72	6.94	0.0530	0.0589	0.1119	299.	766.	6.86	0.0161	0.0	0.0	1326.	1584.	0.46	24.7	0.0	0.0	0.0	0.0	0.0	0.0	1.5		JETA+NAP
220	8.67	6.91	0.0498	0.0669	0.1167	296.	767.	6.81	0.0169	0.0169	1.00	1351.	0.	0.0	24.7	3.38	15.6	34.5	3.1	8.8	98.8	1.6		#2HH
405	4.80	3.81	0.0384	0.0	0.0384	299.	426.	2.85	0.0101	0.0084	0.83	821.	0.	0.0	18.1	1.76	18.3	8.1	5.1	2.8	99.2	1.2		JETA+XYL
406	4.75	3.78	0.0498	0.0	0.0498	299.	429.	2.97	0.0132	0.0114	0.86	935.	0.	0.0	17.3	2.37	17.2	17.0	4.7	4.8	99.1	1.1		JETA+XYL
406	4.84	3.85	0.0493	0.0	0.0493	299.	424.	2.97	0.0128	0.0	0.0	916.	1516.	1.21	17.4	0.0	0.0	0.0	0.0	0.0	0.0	1.1		JETA+XYL
407	4.84	3.85	0.0541	0.0	0.0541	300.	425.	2.98	0.0141	0.0125	0.69	963.	0.	0.0	17.4	2.56	17.0	31.7	4.3	5.2	98.8	0.9		JETA+XYL
408	4.78	3.80	0.0624	0.0	0.0624	299.	431.	2.91	0.0164	0.0147	0.90	1048.	0.	0.0	17.9	2.94	16.3	75.7	3.8	5.1	97.8	0.9		JETA+XYL
418	8.73	6.95	0.0525	0.1030	0.1555	300.	759.	6.85	0.0224	0.0231	1.03	1513.	0.	0.0	24.5	4.76	13.5	9.4	0.6	13.0	99.7	1.4	SN=2	JETA+XYL
419	8.63	6.87	0.0527	0.0842	0.1369	301.	772.	6.85	0.0199	0.0206	1.04	1449.	0.	0.0	24.6	4.23	14.4	14.0	1.3	11.2	99.5	1.4	SN=2	JETA+XYL
420	8.69	6.91	0.0524	0.0717	0.1241	301.	772.	6.85	0.0180	0.0183	1.02	1388.	0.	0.0	24.8	3.75	15.1	25.7	2.3	9.9	99.1	1.4	SN=3	JETA+XYL
421	8.68	6.90	0.0524	0.0574	0.1098	301.	774.	6.85	0.0159	0.0	0.0	1326.	1584.	0.47	24.8	0.0	0.0	0.0	0.0	0.0	0.0	1.4		JETA+XYL
421	8.59	6.83	0.0528	0.0570	0.1098	301.	774.	6.87	0.0161	0.0152	0.94	1331.	0.	0.0	24.5	3.07	16.2	62.2	9.6	8.8	97.4	1.4	SN=3	JETA+XYL
205	4.95	3.93	0.0401	0.0	0.0401	296.	430.	2.97	0.0102	0.0085	0.83	830.	0.	0.0	18.1	1.78	18.2	8.6	3.4	2.9	99.4	0.9		#2HH
206	4.86	3.87	0.0481	0.0	0.0481	296.	428.	2.93	0.0124	0.0105	0.85	908.	0.	0.0	17.9	2.19	17.5	16.9	3.4	4.4	99.2	1.0		#2HH
206	4.83	3.85	0.0483	0.0	0.0483	296.	428.	2.95	0.0125	0.0	0.0	912.	1693.	1.61	17.7	0.0	0.0	0.0	0.0	0.0	0.0	1.1		#2HH
207	4.78	3.80	0.0537	0.0	0.0537	296.	428.	2.93	0.0141	0.0121	0.86	968.	0.	0.0	17.6	2.46	17.0	46.8	3.0	4.9	98.6	1.1		#2HH
208	4.87	3.87	0.0619	0.0	0.0619	296.	431.	2.97	0.0160	0.0145	0.91	1034.	0.	0.0	17.8	2.86	16.2	101.2	2.9	4.7	97.3	1.1		#2HH
218	8.68	6.91	0.0527	0.1010	0.1537	296.	772.	6.49	0.0223	0.0216	0.97	1519.	0.	0.0	26.2	4.47	13.9	9.1	0.7	12.0	99.7	1.4	SN=3	#2HH
219	8.72	6.94	0.0532	0.0845	0.1377	296.	759.	6.90	0.0199	0.0187	0.94	1436.	0.	0.0	24.3	3.87	14.8	17.7	1.9	10.4	99.4	1.6	SN=1	#2HH
221	8.67	6.90	0.0523	0.0567	0.1090	296.	771.	6.79	0.0158	0.0	0.0	1320.	1534.	0.39	24.9	0.0	0.0	0.0	0.0	0.0	0.0	1.5		#2HH
221	8.65	6.89	0.0523	0.0571	0.1094	296.	772.	6.84	0.0159	0.0142	0.89	1323.	0.	0.0	24.7	2.86	16.3	77.9	—	7.6	98.2	1.4	SN=2	#2HH
305	4.86	3.86	0.0382	0.0	0.0382	298.	432.	2.93	0.0099	0.0080	0.81	820.	0.	0.0	18.1	1.65	18.2	7.2	3.8	3.2	99.4	1.1		DIESEL
306	4.91	3.90	0.0487	0.0	0.0487	298.	430.	2.92	0.0125	0.0105	0.84	910.	0.	0.0	18.3	2.17	17.3	19.4	2.5	4.9	99.3	1.1		DIESEL
306	4.87	3.88	0.0494	0.0	0.0494	298.	429.	2.89	0.0127	0.0	0.0	920.	1817.	1.83	18.3	0.0	0.0	0.0	0.0	0.0	0.0	1.1		DIESEL
307	4.87	3.87	0.0535	0.0	0.0535	298.	430.	2.93	0.0138	0.0124	0.90	959.	0.	0.0	18.0	2.49	17.0	46.0	2.2	5.2	98.7	1.1		DIESEL
308	4.92	3.91	0.0629	0.0	0.0629	299.	429.	2.97	0.0161	0.0132	0.82	1035.	0.	0.0	18.0	2.55	16.7	120.5	2.4	4.7	96.9	1.1		DIESEL

Configuration H-7

Point Number	Airflow - Total kg/s	Airflow-Combustor kg/s	Fuel Flow - Pilot kg/s	Fuel Flow - Main kg/s	Fuel Flow - Total kg/s	Fuel Temperature K	Inlet Total Temperature K	Inlet Total Pressure — atm	Fuel-Air Ratio Metered (M)	Fuel-Air Ratio Carbon Balance (CB)	Fuel-Air (CB) / Fuel-Air (M)	Ideal Combustor Exit Temperature K	Maximum Combustor Exit Temperature K	Pattern Factor	Reference Velocity - m/s	CO_2 - % Volume	O_2 - % Volume	CO (EI)	THC (EI)	NO_X (EI)	Gas Sample Combustion Efficiency	Humidity-(g H_2O/kg air)	SAE Smoke Number	Comments
202	8.68	6.90	0.0537	0.1066	0.1605	294.	770.	6.82	0.0233	0.0213	0.91	1548.	0.	0.0	24.7	4.38	14.1	12.2	0.6	12.7	99.6	1.0		#2 HH
2021	8.72	6.93	0.0530	0.1069	0.1599	295.	769.	6.91	0.0231	0.0212	0.92	1541.	0.	0.0	24.6	4.37	14.2	13.4	0.7	12.3	99.6	1.1		#2 HH
2022	8.67	6.91	0.0527	0.1028	0.1555	295.	770.	6.87	0.0225	0.0211	0.94	1525.	0.	0.0	24.7	4.34	14.4	13.2	0.9	12.3	99.6	1.1		#2 HH
2023	8.72	6.93	0.0533	0.1068	0.1601	295.	766.	6.93	0.0231	0.0206	0.89	1540.	0.	0.0	24.3	4.24	14.3	15.2	0.8	12.8	99.6	1.2		#2 HH
2024	8.63	6.87	0.0534	0.1061	0.1595	296.	769.	6.79	0.0232	0.0216	0.93	1545.	0.	0.0	24.7	4.43	14.2	15.4	0.9	13.0	99.5	1.1		#2 HH
2031	4.86	3.85	0.0468	0.0	0.0468	294.	434.	2.89	0.0122	0.0093	0.76	903.	0.	0.0	18.4	1.90	17.9	36.9	5.0	4.0	98.6	1.1		#2 HH
2031	4.88	3.88	0.0473	0.0	0.0473	294.	430.	2.88	0.0122	0.0	0.0	901.	1463.	1.19	18.5	0.0	0.0	0.0	0.0	0.0	0.0	1.1		#2 HH
2032	4.92	3.91	0.0472	0.0	0.0472	294.	430.	2.91	0.0121	0.0091	0.75	897.	0.	0.0	18.4	1.88	18.0	32.8	2.8	4.2	98.9	1.1		#2 HH
2032	4.95	3.94	0.0474	0.0	0.0474	294.	430.	2.89	0.0120	0.0	0.0	895.	1455.	1.20	18.7	0.0	0.0	0.0	0.0	0.0	0.0	1.1		#2 HH
2033	4.85	3.85	0.0471	0.0	0.0471	289.	430.	2.92	0.0122	0.0091	0.75	903.	0.	0.0	18.0	1.87	18.0	33.0	2.5	4.4	98.9	1.1		#2 HH
2033	4.89	3.88	0.0473	0.0	0.0473	294.	430.	2.89	0.0122	0.0	0.0	900.	1454.	1.18	18.3	0.0	0.0	0.0	0.0	0.0	0.0	1.2		#2 HH
2034	4.82	3.83	0.0472	0.0	0.0472	294.	428.	2.89	0.0123	0.0093	0.76	904.	0.	0.0	18.0	1.90	18.0	37.1	1.9	4.5	98.9	1.1		#2 HH
2034	4.86	3.86	0.0473	0.0	0.0473	289.	428.	2.88	0.0122	0.0	0.0	900.	1503.	1.28	18.3	0.0	0.0	0.0	0.0	0.0	0.0	1.1		#2 HH
2035	4.89	3.88	0.0474	0.0	0.0474	293.	428.	2.91	0.0122	0.0092	0.75	900.	0.	0.0	18.1	1.88	18.0	39.7	1.9	4.6	98.9	1.1		#2 HH
2035	4.88	3.88	0.0473	0.0	0.0473	293.	428.	2.87	0.0122	0.0	0.0	899.	1539.	1.36	18.4	0.0	0.0	0.0	0.0	0.0	0.0	1.1		#2 HH

Configuration S-20

Point Number	Airflow - Total kg/s	Airflow-Combustor kg/s	Fuel Flow - Pilot kg/s	Fuel Flow - Main kg/s	Fuel Flow - Total kg/s	Fuel Temperature K	Inlet Total Temperature K	Inlet Total Pressure – atm	Fuel-Air Ratio Metered (M)	Fuel-Air Ratio Carbon Balance (CB)	Fuel-Air (CB) / Fuel-Air (M)	Ideal Combustor Exit Temperature K	Maximum Combustor Exit Temperature K	Pattern Factor	Reference Velocity - m/s	CO_2 - % Volume	O_2% - Volume	CO (EI)	THC (EI)	NO_X (EI)	Gas Sample Combustion Efficiency	Humidity (g H_2O/kg air)	SAE Smoke Number	Comments
2	4.90	3.89	0.0476	0.0	0.0476	306.	430.	2.95	0.0122	0.0	0.0	903.	1090.	0.40	31.4	0.0	0.0	0.0	0.0	0.0	0.0	2.1		JETA
2	4.86	3.86	0.0477	0.0	0.0477	306.	427.	2.94	0.0123	0.0094	0.76	903.	0.	0.0	30.9	1.88	17.7	45.6	6.2	3.5	98.2	2.2		JETA
3	4.95	3.93	0.0610	0.0	0.0610	305.	427.	2.95	0.0155	0.0122	0.79	1013.	0.	0.0	31.2	2.42	17.1	46.6	7.7	4.0	98.0	2.0		JETA
4	4.88	3.89	0.0305	0.0	0.0305	306.	426.	2.94	0.0078	0.0061	0.78	738.	0.	0.0	31.1	1.22	18.5	35.4	9.3	2.8	98.1	1.9		JETA
5	4.92	3.92	0.0230	0.0	0.0230	306.	428.	2.94	0.0059	0.0047	0.80	665.	0.	0.0	31.5	0.90	19.5	91.3	29.8	1.9	94.4	1.7		JETA
16	8.65	6.88	0.0306	0.1194	0.1500	306.	769.	6.84	0.0218	0.0278	1.28	1501.	0.	0.0	42.7	5.49	12.1	30.8	0.4	9.6	99.2	2.6	SN=4	JETA
19	8.62	6.86	0.0310	0.0930	0.1240	307.	766.	6.87	0.0181	0.0237	1.31	1388.	0.	0.0	42.4	4.76	13.5	15.6	0.1	9.4	99.6	2.9	SN=1	JETA
20	8.68	6.91	0.0307	0.0786	0.1093	307.	768.	6.83	0.0156	0.0135	1.17	1318.	0.	0.0	42.9	3.75	14.8	9.8	0.3	6.5	99.7	2.7	SN=1	JETA
20	8.71	6.93	0.0307	0.0783	0.1090	307.	768.	6.82	0.0157	0.0	0.0	1314.	1671.	0.65	43.1	0.0	0.0	0.0	0.0	0.0	0.0	2.7		JETA

Configuration S-20 (Cont'd)

Point Number	Airflow - Total kg/s	Airflow-Combustor kg/s	Fuel Flow - Pilot kg/s	Fuel Flow - Main kg/s	Fuel Flow - Total kg/s	Fuel Temperature K	Inlet Total Temperature K	Inlet Total Pressure – atm	Fuel-Air Ratio Metered (M)	Fuel-Air Ratio Carbon Balance (CB)	Fuel-Air (CB) / Fuel-Air (M)	Ideal Combustor Exit Temperature K	Maximum Combustor Exit Temperature K	Pattern Factor	Reference Velocity - m/s	CO_2 - % Volume	O_2% - Volume	CO (EI)	THC (EI)	NO_X (EI)	Gas Sample Combustion Efficiency	Humidity (g H_2O/kg air)	SAE Smoke Number	Comments
202	4.94	3.93	0.0490	0.0	0.0490	303.	427.	2.94	0.0125	0.0101	0.81	908.	0.	0.0	31.5	2.00	17.4	66.8	10.2	4.0	97.3	1.1		#2HH
203	4.95	3.94	0.0626	0.0	0.0626	303.	425.	2.93	0.0150	0.0122	0.77	1025.	0.	0.0	31.6	2.45	16.3	77.0	10.8	3.2	97.0	1.1		#2HH
204	4.93	3.91	0.0309	0.0	0.0309	304.	427.	2.94	0.0079	0.0065	0.82	742.	0.	0.0	31.4	1.33	17.4	51.2	7.5	3.1	97.9	1.1		#2HH
205	4.92	3.91	0.0234	0.0	0.0234	304.	426.	2.94	0.0060	0.0050	0.83	668.	0.	0.0	31.3	0.95	18.1	147.0	40.2	2.1	91.9	1.1		#2HH
218	8.66	6.90	0.0308	0.1241	0.1549	304.	768.	6.87	0.0224	0.0262	1.17	1521.	0.	0.0	42.6	5.37	12.6	18.2	0.4	9.2	99.5	1.4	SN=6	#2HH.
219	8.72	6.94	0.0308	0.1051	0.1359	304.	768.	6.67	0.0196	0.0227	1.16	1435.	0.	0.0	44.3	4.68	13.0	14.7	0.6	8.4	99.6	1.4	SN=2	#2HH
220	8.74	6.96	0.0308	0.0786	0.1094	305.	767.	6.78	0.0157	0.0	0.0	1314.	1730.	0.76	43.5	0.0	0.0	0.0	0.0	0.0	0.0	1.4	SN=3	#2HH
221	8.68	6.92	0.0314	0.0656	0.0970	305.	768.	6.78	0.0140	0.0156	1.11	1260.	0.	0.0	43.3	3.22	15.8	18.9	1.2	7.7	99.4	1.3	SN=3	#2HH
402	4.93	3.91	0.0480	0.0	0.0480	304.	434.	2.89	0.0123	0.0102	0.83	908.	0.	0.0	32.5	2.07	17.6	68.7	6.9	4.1	97.6	1.1		JETA+XYL
402	5.01	3.98	0.0480	0.0	0.0480	304.	429.	2.91	0.0121	0.0	0.0	896.	1054.	0.34	32.5	0.0	0.0	0.0	0.0	0.0	0.0	1.1		JETA+XYL
403	4.98	3.97	0.0613	0.0	0.0613	303.	429.	2.98	0.0154	0.0131	0.85	1014.	0.	0.0	31.5	2.62	16.7	74.9	7.8	3.0	97.4	1.2		JETA+XYL
404	5.01	3.99	0.0302	0.0	0.0302	303.	429.	2.91	0.0076	0.0066	0.87	731.	0.	0.0	32.5	1.35	19.0	44.2	8.5	2.9	98.0	1.3		JETA+XYL
405	5.01	3.98	0.0237	0.0	0.0237	303.	424.	2.91	0.0060	0.0052	0.87	665.	0.	0.0	32.0	1.01	19.7	110.0	27.6	1.9	94.2	1.2		JETA+XYL
202	4.97	3.95	0.0490	0.0	0.0490	303.	425.	2.93	0.0124	0.0	0.0	904.	1044.	0.29	31.7	0.0	0.0	0.0	0.0	0.0	0.0	1.1		#2HH
418	8.74	6.95	0.0306	0.1229	0.1535	303.	768.	6.87	0.0221	0.0269	1.22	1511.	0.	0.0	43.0	5.48	12.5	22.3	0.0	10.0	99.5	1.1		JETA+XYL
419	8.63	6.86	0.0311	0.1063	0.1374	303.	769.	6.80	0.0200	0.0233	1.16	1450.	0.	0.0	42.8	4.80	13.3	13.8	0.0	9.8	99.7	1.1		JETA+XYL
420	8.65	6.88	0.0312	0.0785	0.1097	304.	770.	6.85	0.0159	0.0	0.0	1324.	1704.	0.69	42.8	0.0	0.0	0.0	0.0	0.0	0.0	1.1	SN=6	JETA+XYL
420	8.58	6.83	0.0303	0.0794	0.1097	304.	772.	6.89	0.0161	0.0183	1.14	1329.	0.	0.0	42.2	3.79	15.3	13.1	0.0	9.0	99.7	1.1	SN=4	JETA+XYL
421	8.69	6.92	0.0306	0.0676	0.0982	306.	771.	6.80	0.0142	0.0160	1.13	1269.	0.	0.0	43.4	3.32	16.0	9.4	0.7	8.3	99.7	1.0	SN=4	JETA+XYL
419	8.61	6.84	0.0336	0.1062	0.1398	306.	772.	6.70	0.0204	0.0230	1.13	1466.	0.	0.0	43.6	4.73	13.5	15.3	0.6	9.7	99.6	0.1		JETA+XYL
502	4.88	3.88	0.0483	0.0	0.0483	305.	424.	3.05	0.0124	0.0104	0.84	906.	0.	0.0	29.7	2.13	17.7	44.0	4.1	4.2	98.5	0.4		JETA+NAP
502	4.89	3.89	0.0482	0.0	0.0482	305.	425.	3.03	0.0124	0.0	0.0	904.	1053.	0.31	30.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1		JETA+NAP
503	4.85	3.85	0.0610	0.0	0.0610	305.	426.	3.03	0.0158	0.0135	0.85	1024.	0.	0.0	29.8	2.76	16.8	53.6	3.5	2.9	98.4	1.3		JETA+NAP
504	4.84	3.85	0.0302	0.0	0.0302	306.	427.	2.99	0.0079	0.0066	0.84	740.	0.	0.0	30.3	1.37	19.0	32.9	6.1	2.5	98.5	1.3		JETA+NAP
505	4.91	3.90	0.0236	0.0	0.0236	306.	424.	2.98	0.0061	0.0051	0.84	669.	0.	0.0	30.6	0.99	19.6	103.5	34.1	1.7	93.6	1.3		JETA+NAP
518	8.64	6.88	0.0299	0.1211	0.1510	306.	765.	6.95	0.0220	0.0277	1.26	1504.	0.	0.0	41.8	5.61	12.5	29.2	0.4	9.1	99.3	1.8	SN=16	JETA+NAP
519	8.72	6.94	0.0299	0.1073	0.1372	308.	767.	6.89	0.0198	0.0237	1.20	1440.	0.	0.0	42.7	4.86	13.6	17.4	0.3	8.5	99.6	1.9	SN=23	JETA+NAP
520	8.70	6.92	0.0308	0.0785	0.1093	308.	768.	6.84	0.0158	0.0	0.0	1318.	1679.	0.66	43.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8		JETA+NAP
520	8.68	6.91	0.0308	0.0785	0.1093	309.	770.	6.93	0.0158	0.0193	1.22	1320.	0.	0.0	42.4	4.00	15.1	11.2	0.5	7.7	99.7	1.8	SN=5	JETA+NAP
521	8.71	6.92	0.0308	0.0626	0.0934	309.	767.	6.68	0.0135	0.0162	1.20	1243.	0.	0.0	42.6	3.36	16.0	12.1	0.6	7.8	99.6	1.8	SN=3	JETA+NAP
5211	8.65	6.88	0.0307	0.0633	0.0940	308.	768.	6.90	0.0137	0.0167	1.22	1249.	0.	0.0	42.3	3.46	15.5	11.1	0.5	7.6	99.7	1.8		JETA+NAP
302	4.88	3.68	0.0487	0.0	0.0487	303.	426.	2.93	0.0125	0.0	0.0	910.	1086.	0.36	31.2	0.0	0.0	0.0	0.0	0.0	0.0	1.5		DIESEL
302	4.92	3.91	0.0484	0.0	0.0484	303.	429.	2.96	0.0124	0.0100	0.81	906.	0.	0.0	31.3	2.02	17.8	52.7	10.6	3.7	97.6	1.6		DIESEL
303	4.86	3.86	0.0616	0.0	0.0616	304.	429.	2.96	0.0160	0.0133	0.83	1030.	0.	0.0	30.8	2.57	17.0	71.2	12.8	2.9	96.9	1.6		DIESEL
304	4.95	3.94	0.0308	0.0	0.0308	303.	427.	2.93	0.0078	0.0063	0.81	739.	0.	0.0	31.6	1.29	19.1	34.3	9.9	2.8	98.1	1.7		DIESEL
305	4.97	3.95	0.0230	0.0	0.0230	304.	427.	2.97	0.0058	0.0047	0.81	662.	0.	0.0	31.3	0.91	19.6	108.1	40.8	2.0	92.8	1.8		DIESEL
318	8.63	6.87	0.0312	0.1229	0.1541	307.	770.	6.91	0.0224	0.0309	1.38	1522.	0.	0.0	42.2	6.15	11.2	35.4	0.5	9.9	99.1	2.5	SN=4	DIESEL
319	8.58	6.83	0.0272	0.1093	0.1365	307.	765.	6.96	0.0200	0.0269	1.34	1443.	0.	0.0	41.4	5.43	12.5	18.5	0.5	9.6	99.5	2.5	SN=2	DIESEL
320	8.74	6.96	0.0214	0.0876	0.1090	308.	765.	6.87	0.0157	0.0190	1.21	1310.	0.	0.0	42.8	3.83	15.0	35.2	7.6	7.9	98.3	2.3	SN=2	DIESEL
320	8.68	6.92	0.0214	0.0878	0.1092	308.	768.	6.91	0.0158	0.0	0.0	1316.	1698.	0.70	42.4	0.0	0.0	0.0	0.0	0.0	0.0	2.3		DIESEL
321	8.72	6.94	0.0192	0.0758	0.0950	307.	764.	6.93	0.0137	0.0161	1.18	1246.	0.	0.0	42.3	3.21	16.0	50.6	20.3	7.0	96.5	2.1	SN=2	DIESEL
320	8.55	6.82	0.0302	0.0795	0.1097	303.	766.	6.70	0.0161	0.0	0.0	1325.	1589.	0.47	43.1	0.0	0.0	0.0	0.0	0.0	0.0	1.2		DIESEL
320	8.76	6.97	0.0309	0.0815	0.1124	305.	768.	6.70	0.0161	0.0166	1.03	1328.	0.	0.0	44.3	3.42	15.5	15.5	1.5	8.0	99.5	1.5	SN=4	DIESEL
321	8.68	6.89	0.0300	0.0661	0.0961	305.	770.	6.80	0.0139	0.0134	0.96	1260.	0.	0.0	43.2	2.75	16.4	17.9	1.4	7.3	99.4	1.4	SN=1	DIESEL

Configuration S-22

Point Number	Airflow - Total kg/s	Airflow - Combustor kg/s	Fuel Flow - Pilot kg/s	Fuel Flow - Main kg/s	Fuel Flow - Total kg/s	Fuel Temperature K	Inlet Total Temperature K	Inlet Total Pressure – atm	Fuel-Air Ratio Metered (M)	Fuel-Air Ratio Carbon Balance (CB)	Fuel-Air (CB) / Fuel-Air (M)	Ideal Combustor Exit Temperature K	Maximum Combustor Exit Temperature K	Pattern Factor	Reference Velocity - m/s	CO_2 - % Volume	O_2 - % Volume	CO (EI)	THC (EI)	NO_X(EI)	Gas Sample Combustion Efficiency	Humidity (g H_2O/kg air)	SAE Smoke Number	Comments
2	8.65	6.69	0.0141	0.1384	0.1525	288.	774.	6.85	0.0221	0.0284	1.29	1519.	0.	0.0	43.0	5.61	12.6	31.9	2.9	8.9	98.9	0.0		#2HH
21	8.63	6.87	0.0141	0.1378	0.1519	289.	772.	6.79	0.0221	0.0284	1.29	1516.	0.	0.0	43.1	5.60	12.4	30.8	2.9	9.1	98.9	0.0		#2HH
22	8.68	6.91	0.0139	0.1377	0.1516	289.	770.	6.80	0.0220	0.0291	1.32	1510.	0.	0.0	43.2	5.74	12.4	30.1	2.9	9.3	99.0	0.0		#2HH
23	8.67	6.89	0.014[illegible]	0.1379	0.1519	289.	772.	6.80	0.0220	0.0295	1.34	1515.	0.	0.0	43.2	5.81	12.2	33.5	3.6	9.2	98.8	0.0		#2HH
24	8.66	6.88	0.0140	0.1382	0.1522	293.	774.	6.83	0.0221	0.0296	1.31	1519.	0.	0.0	43.1	5.72	12.3	32.7	3.7	9.4	98.8	0.0		#2HH
3	4.94	3.93	0.0507	0.0	0.0507	291.	429.	2.94	0.0129	0.0097	0.75	926.	0.	0.0	31.7	1.93	18.0	60.5	3.4	3.5	98.2	0.0		#2HH
3	4.94	3.92	0.0507	0.0	0.0507	291.	428.	2.91	0.0129	0.0	0.0	926.	1161.	0.47	31.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
3	4.91	3.90	0.0508	0.0	0.0508	290.	429.	2.94	0.0130	0.0096	0.74	930.	0.	0.0	31.4	1.91	17.9	60.7	3.2	3.5	98.2	0.0		#2HH
3	4.93	3.91	0.0507	0.0	0.0507	290.	429.	2.93	0.0129	0.0	0.0	928.	1224.	0.59	31.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
3	4.92	3.91	0.0507	0.0	0.0507	290.	428.	2.98	0.0130	0.0099	0.76	928.	0.	0.0	31.0	1.97	17.8	58.6	3.0	3.4	98.3	0.0		#2HH
3	4.91	3.90	0.0506	0.0	0.0506	290.	428.	2.96	0.0130	0.0	0.0	928.	1160.	0.46	31.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
3	4.98	3.95	0.0506	0.0	0.0506	290.	428.	2.96	0.0128	0.0098	0.77	923.	0.	0.0	31.5	1.95	17.9	62.4	2.7	3.4	98.2	0.0		#2HH
3	4.94	3.90	0.0506	0.0	0.0506	290.	428.	2.94	0.0130	0.0	0.0	928.	1215.	0.57	31.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
3	4.90	3.89	0.0503	0.0	0.0503	290.	429.	2.97	0.0130	0.0091	0.70	928.	0.	0.0	31.0	1.81	18.1	58.2	3.0	3.5	98.3	0.0		#2HH
3	4.94	3.93	0.0506	0.0	0.0506	290.	428.	2.95	0.0129	0.0	0.0	925.	1209.	0.57	31.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0		

APPENDIX D

APPENDIX D

ALTITUDE STABILITY TEST RESULTS
FOR HYBRID COMBUSTOR CONFIGURATION H-6

Combustor Operating Conditions at the Minimum Pressure Blow Out (MPBO)

Point Number	Airflow Total kg/sec	Fuel Flow Total kg/sec	Fuel Temperature K	Inlet Air Total Temperature K	Inlet Total Pressure atm	Inlet Air Dew Point K	Fuel Type
1	0.725	0.0208	297	244	0.199	294	Jet A
2	0.841	0.0208	297	250	0.242	294	Jet A
3	0.992	0.0208	297	260	0.247	294	Jet A
4	1.229	0.0208	297	267	0.280	294	Jet A
5	0.670	0.0208	297	243	0.206	288	No. 2 H.H.
6	0.847	0.0208	295	250	0.340	288	No. 2 H.H.
7	0.856	0.0208	296	250	0.327	287	No. 2 H.H.
8	1.028	0.0208	295	260	0.371	287	No. 2 H.H.
9	1.028	0.0208	295	260	0.375	287	No. 2 H.H.
10	1.245	0.0208	294	267	0.601	285	No. 2 H.H.
11	1.245	0.0208	294	267	0.618	285	No. 2 H.H.
12	0.675	0.0208	294	243	0.272	288	No. 2 H.H.

APPENDIX D (Cont'd)

ALTITUDE STABILITY TEST RESULTS
FOR VORBIX COMBUSTOR CONFIGURATION S-20

Combustor Operating Conditions at the Minimum Pressure Blow Out (MPBO)

Point Number	Airflow Total kg/sec	Fuel Flow Total kg/sec	Fuel Temperature K	Inlet Air Total Temperature K	Inlet Total Pressure atm	Inlet Air Dew Point K	Fuel Type
4	1.25	0.0208	293	268	0.380	284	Jet A
9	1.25	0.0208	293	268	0.380	284	Jet A
3	1.06	0.0208	293	261	0.340	284	Jet A
6	1.06	0.0208	293	261	0.340	284	Jet A
10	0.84	0.0208	293	250	0.317	283	Jet A
12	0.84	0.0208	293	250	0.327	283	Jet A
15	0.64	0.0208	293	242	0.267	283	Jet A
16	0.64	0.0208	293	242	0.273	283	Jet A
30	0.79	0.0208	292	250	0.317	286	No. 2 H.H.
31	0.79	0.0208	292	250	0.327	286	No. 2 H.H.
32	0.67	0.0208	292	242	0.270	287	No. 2 H.H.
33	0.67	0.0208	292	242	0.270	287	No. 2 H.H.
34	1.01	0.0208	292	261	0.337	287	No. 2 H.H.
35	1.01	0.0208	292	261	0.337	287	No. 2 H.H.
36	1.25	0.0208	293	268	0.370	287	No. 2 H.H.
37	1.25	0.0208	293	268	0.377	288	No. 2 H.H.

APPENDIX E

DISTRIBUTION LIST

I. NASA

1. NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
Attn: Report Control Office 1
MS 5/5
Technology Utilization
MS 3/19 1
Library MS 60/3 2
Fluid Sys. Components Div.
MS 5/3 1
L. Schopen MS 500/206 1
J. B. Esgar MS 60/4 1
R. A. Rudey MS 60/6 1
R. E. Jones MS 60/6 1
J. Grobman MS 60/6 1
J. Acurio MS 77/5 1
Maj. Gasperich MS 501/3 1
Patent Counsel N. T. Musial
MS 500/113 1
W. L. Stewart MS 3/5 1

2. NASA Langley Research Center
Langley Station
Hampton, VA 23365
Attn: Dr. C. J. Jachimowski
MS 419A 1

3. NASA Headquarters
600 Independence Ave. S.W.
Washington, DC 20546
Attn: RL/H. Johnson 1
RL/N. Rekos 1
RL/D. Miller 1
RT/W. Aiken 1
RL/G. Banerian 1

4. NASA Scientific & Technical Information Facility 10
Attn: NASA Representative
P. O. Box 33
College Park, MD 20740
RQT 2448

II. OTHER GOVERNMENT AGENCIES

1. FAA Headquarters
800 Independence Ave., S. W.
Washington, DC 20591
Attn: K. Forney AFS-141 1
Attn: Library (2100 2nd St. S.W.) 1
W. Westfield ARD-550 1

2. United States Army
Mr. Kent Smith, SAVDL/DU-TAT 1
Commanding Officer
Eustis Directorate - USA AMRDL
Fort Eustis, VA 23604

3. United States Army
Mr. Larry Bell 1
AVSCOM, AMSAV-EFP
Box 209
St. Louis, MO 63166

4. Air Force Office of Scientific Research
1400 Wilson Boulevard
Arlington, VA 22209
Attn: T. Wolfson 1

5. Defense Documentation Center (DDC) 1
Cameron Station
5010 Duke Street
Alexandria, VA 22314

6. Environmental Protection Agency
401 Main Street S.W.
Washington, DC 20460
Attn: George Kittredge 1

7. Environmental Protection Agency
2565 Plymouth Road
Ann Arbor, MI 48105
Attn: Richard Munt 1
Gary Austin 1
Bill Houtman 1

APPENDIX E

8. Naval Air Propulsion Test Center
Trenton, NJ 03628
Attn: Anthony Klarman (TE-43) 1
Bill Wagner (TE-43) 1
Larry Magitti (PE-71) 1

9. U. S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge, MA 02142
Attn: Anthony J. Broderick 1

10. Wright-Patterson Air Force Base
OH 45433
Attn: Len Obery NASA/AFAPL
Liaison 1
Dr. William S. Blazowski
AFAPL/SFF 1
Area B, Bldg. 18D
Robert Henderson AFAPL/TBC 1
Area B, Bldg. 18D
Charles Delaney 1

11. Environmental Protection Agency
Research Triangle Park, NC 27711
Mail Drop 65
Attn: John H. Wasser 1
W. S. Lanier 1

12. Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103
Attn: Jack H. Rupe
MS 125-224 1

13. Bureau of Mines
Bartlesville Energy Research Center
P. O. Box 1398
Bartlesville, OK 74003
Attn: Richard Hurn 1

14. Naval Ordnance Systems Command
Department of the Navy
Arlington, VA 20360
Attn: John W. Murrin 1

15. Institute for Defense Analysis
400 Army-Navy Drive
Arlington, VA 22202
Attn: Dr. Robert C. Oliver 1

16. Arnold Engineering & Development
Center
AF Arnold Station, TN 37389
Attn: E. L. Hively Code D1/R 1

17. ARO Incorporated
Arnold Air Force Station
TN 37389
Attn: Library 1

18. Fossil Energy, ERDA
20 Massachusetts Avenue
Washington, DC 20402
Attn: Dr. Herman L. Finke 1
John L. Morris 1

19. U. S. Army Mobility Equipment
Research & Development Center
Ft. Delvoir, VA 22060
Attn: Maurice E. Lepera 1

20. Naval Ship Research & Development
Center
Annapolis Laboratory
Annapolis, MD 21402
Attn: Lt. Larry Lukens (071) 1

21. Department of the Navy
Headquarters Naval Material
Command
Washington, DC 20360
Attn: Capt. V. M. Skrinak 1
032-SHZ

22. U. S. Army Field & Lubrication
Research Laboratory
Southwest Research Institute
8500 Culabra Road
San Antonio, TX
Attn: Cliff Moses 1

23. Department of the Army
U. S. Tank Automotive Command
Warren, MI 48090
Attn: Ernest E. Marsh

24. Aircraft Environment Support Office
Naval Air System Command
Naval Air Rework Facility
North Island, San Diego, CA
Attn: Dr. Wendy Cook 1

III. UNIVERSITIES

1. The Johns Hopkins University
Applied Physics Laboratory
8621 Georgia Avenue
Silver Springs, MD 20910
Attn: G. Dugger 1

2. Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
Attn: Prof. J. Heywood 1

3. University of Cincinnati
Department of Aerospace Engineering
Cincinnati, OH 45221
Attn: Prof. W. Kauffman 1

4. University of California
Department of Mechanical Engineering
Berkeley, CA 94720
Attn: Prof. R. F. Sawyer 1

5. Purdue University
School of Mechanical Engineering
West Lafayette, IN 47907
Attn: Prof. A. M. Mellor 1

6. Cornell University
Sibley School of Mechanical & Applied Engineering
Upson & Grumman Halls
Ithaca, NY 14850
Attn: Prof. Sidney Liebovich 1

7. Northwestern University
Department of Mechanical Engineering & Astronautical Sciences
Evenston, IL 60601
Attn: Prof. A. A. Kovitz 1

8. University of Illinois at Urbana Champaign
Department of Aeronautical & Astronautical Engineering
101 Transportation Building
Urbana, IL 61801
Attn: Prof. R. A. Strehlow 1

9. University of California Los Angeles
School of Engineering & Applied Science
Los Angeles, CA 90024
Attn: Prof. J. M. English 1

10. Purdue University
School of Aeronautics & Astronautics
West Lafayette, IN 47907
Attn: Prof. M. P. Felix 1

IV. CORPORATIONS – U.S.

1. Calspan Corporation
4455 Genessee Street
Buffalo, NY 14221 1

2. Teledyne CAE
1330 Laskey Road
Toledo, OH 43697
Attn: Lawrence A. Chuslo 1

3. Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 02140
Attn: Mr. Karl Bastress 1

4. Detroit Diesel Allison Division
Department 8894, Plant 8
P. O. Box 894
Indianapolis, IN 46206
Attn: Frank Verkamp 1
G. Tomlinson 1
Library 1

5. Northern Research & Engineering Corporation
219 Vassar Street
Cambridge, MA 02139
Attn: E. R. Norster 1

6. Turbodyne Corporation
711 Anderson Avenue
St. Cloud, MN 56301
Attn: Mr. K. Hanson 1

7. Advanced Technology Laboratories
Merrick and Stevens Avenue
Westbury, NY 11590
Attn: J. Roffe 1

8. General Electric Company
100 Western Avenue
West Lynn, MA 01905
Attn: Library Building 1
Dr. C. W. Smith, 2-40M 1

9. Curtiss-Wright Corporation
One Passaic Street
Woodridge, NJ 07075
Attn: S. Moskowitz 1

10. AiResearch Manufacturing Company
2525 W. 190 Street
Torrance, CA 90509
Attn: L. C. Wright 1

11. AVCO Corporation
Lycoming Division
550 South Main Street
Stratford, CT
Attn: N. R. Marchionna 1
G. Opdyke 1

12. International Harvester Company
Solar Division
2200 Pacific Highway
San Diego, CA 92112
Attn: W. A. Compton 1

13. The Boeing Company
Commercial Airplane Division
P. O. Box 3991
Seattle, WA 98124
Attn: C. B. Stewart MS 73-07 1
I. Thomas 1

14. Garrett/AiResearch Company
402 South 36th Street
Phoenix, AZ 85034
Attn: J. M. Haasis 1
K. Johannsen 1

15. Westinghouse Electric Corporation
Research and Development Center
Pittsburgh, PA 15235
Attn: Mr. Richard M. Chamberlain 1

16. Westinghouse Electric Corporation
Gas Turbine Systems Division
Lester Branch
Box 9175
Philadelphia, PA 19113
Attn: Mr. S. M. DelCorso 1

17. Douglas Aircraft Company
3855 Lakewood Blvd.
Long Beach, CA 90801
Attn: Mr. W.R. Dunbar (36-41) 1
A. T. Peacock 1

18. Lockheed California Company
Lockheed Aircraft Corporation
Burbank, CA
Attn: E. F. Versaw 1

19. Applied Systems Corporation
215 Mill Street
Vienna, VA 22180
Attn: H. Bartick 1

20. United Technologies Corporation
Pratt & Whitney Aircraft Division
400 Main Street
East Hartford, CT 06108
Attn: R. Marshall 1
P. Goldberg 1
Library 1
R. Roberts 1
A. R. Marsh 1

21. United Technologies Corporation
Pratt & Whitney Aircraft Division
Florida Research & Development Ctr.
Box 2691
West Palm Beach, FL 33402
Attn: G. Lewis 1
S. Mosier 1

22. Cameron Engineers
1315 South Clarkson Street
Denver, CO 80210
Attn: G. L. Baughman 1

23. United Airlines
San Francisco, CA
Attn: Paul Campbell 1

24. Phillips Petroleum Company
Bartlesville, OK 74004
Attn: R. M. Schirmer R&D 1

25. American Airlines 1
3500 North Mingo Road
Tulsa, OK 74151
Attn: J. K. Siddons

26. AiResearch Manufacturing Company
of Arizona
P. O. Box 5217
Phoenix, AZ 85010
Attn: Dr. H. C. Mongia 1

27. General Electric Company
Flight Propulsion Division
Cincinnati, OH 45215
Attn: C. Danforth H-32
D. Bahr H-33
Technical Information Ctr N-32
C. C. Gleason H-33

REFERENCES

1. Roberts, R., Peduzzi, A., Vitti, G.,: "Experimental Clean Combustor Program," Phase II Final Report, NASA CR-134969.

2. Roberts, R., Peduzzi, A... Vitti, G.,: "Experimental Clean Combustor Program," Phase I Final Report, NASA CR-134736, October 1975.

3. "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," SAE Aerospace Recommended Practice 1256, October 1975.

4. "Aircraft Gas Turbine Engine Exhaust Smoke Measurement," SAE Aerospace Recommended Practice 1179, May 1970.

5. Environmental Protection Agency: "Control of Air Pollution from Aircraft and Aircraft Engines; Emission Standards and Test Procedures for Aircraft," Federal Register 38 (136) Part II: 19076 (July 17, 1973).

6. Sarli, V. J., Eiler, D. C., Marshall, R. L.,: "Effects of Operating Variables on Gaseous Emissions," Air Pollution Control Association Conference, New Orleans, Louisiana, October 1975.